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EMERGING ROLE OF POSTBIOTICS IN DAIRY BEVERAGES: A CRITICAL REVIEW OF FUNCTIONAL, NUTRITIONAL AND TECHNOLOGICAL PERSPECTIVES

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HIGHLIGHTS OF THE STUDY:

- Postbiotics represent stable and safe functional ingredients derived from the microbial fermentation
- Dairy beverages provide an effective matrix for the postbiotic delivery due to nutritional synergy and fermentation properties
- Postbiotic compounds exhibit antimicrobial, antioxidant, immunomodulatory, and gut barrier protective effects
- Technological advancements enables the improved stability, shelf life, and formulation flexibility of the postbiotic dairy beverages
- Future research should focus on the clinical validation, metabolite profiling, standardization, and also sustainable production strategies

ABSTRACT

The increasing demand for functional foods has encouraged the exploration of bioactive compounds capable of delivering health benefits while maintaining product safety and stability. In recent years, Postbiotics have increased attention as fermentation-derived bioactive compounds produced by microorganisms. Unlike Probiotics, it requires viable cells to exert beneficial effects, postbiotics consist of non-viable microbial cells and metabolites such as organic acids, bioactive peptides, bacteriocins, short-chain fatty acids and cell wall fragments that retain physiological activity even after microbial inactivation. Because of these properties, Postbiotics are very stable and technologically suitable to add in food systems. Postbiotics demonstrate a wide range of functional and nutritional properties including antimicrobial and antioxidant activities, improvement of gut barrier integrity, immune modulation, enhanced mineral absorption, anti-inflammatory effects and improved digestibility. The bioactivities of these substances increase their importance in the development of functional beverages. Because of their high levels of consumer acceptance, the favourable fermentation conditions, and the nutrient-dense content, dairy drinks are a perfect carrier for postbiotics. Beverages made from milk, fermented dairy products, whey drinks, yoghurt, and kefir are all beneficial for the development of postbiotics and offer both nutritional value and sensory appeal. Their inclusion into dairy beverages has been made easier by technological advancements in fermentation and formulations, which have improved shelf stability and sensory quality. However, the inadequate metabolite characterisation and clinical validation indicate the need for additional research to facilitate widespread usage and product innovation.

Keywords: Postbiotics, Dairy beverages, Functional foods, Bioactive metabolites, Gut health

INTRODUCTION

Over the past decade, the functional food sector has grown rapidly. This growth has mainly happened because people are becoming more aware of how their everyday food choices can influence long-term health. These foods are widely considered a useful dietary approach for lowering the risk of long-term health conditions such as metabolic disorders, gastrointestinal diseases, and problems related to the immune system. Among the different functional ingredients used in these products, probiotics have received a great deal of attention for many years. Probiotics are well known for their ability to support a healthy balance of gut microbiota, improve digestion, and influence immune responses in the body. Because of these benefits, probiotic ingredients have been widely used in many functional food products and dietary supplements. One major challenge in Probiotics is maintaining the survival of probiotic microorganisms during food processing, product storage, and their passage through the gastrointestinal tract after they are consumed. Probiotic bacteria are sensitive to many environmental conditions such as temperature changes, oxygen, and acidic foods that can reduce probiotics. When the number of live probiotic cells goes down, their health benefits also go down. Also, live microbes may not be safe for some people, especially those with weak immunity. Because of this, researchers are looking for other options that can give similar benefits without using live microbes. (Hill et al., 2014; Lebeer et al., 2018)

In this case, the paradigm shift from Probiotics to Postbiotics occurs. Postbiotics are made up of dead microbes that have useful compounds that were made during fermentation. The microbes aren't alive, but they can still give good health benefits. A main advantage is that they do not need to be alive to work. So, they are more stable when being processed & stored, and conditions that generally destroy the living bacteria don't quickly weaken their function. (Tripathi & Giri, 2014; Champagne et al., 2011)

This makes postbiotics easier to use in the food products and may help to improve the stability and shelf life of functional foods. In addition, since postbiotics do not contain live microorganisms, some of the safety concerns that may arise with probiotics can be reduced, especially for people with weakened immune systems. Postbiotics contain many types of bioactive substances formed during microbial metabolism and fermentation. These include organic acids, bioactive peptides, bacteriocins, short-chain fatty acids, exopolysaccharides, enzymes, and fragments of microbial cell walls. Because of this wide range of components, postbiotics can show several useful physiological activities such as antimicrobial effects, antioxidant activity, regulation of immune responses, and anti-inflammatory properties (Salminen et al., 2021; Aguilar-Toala et al., 2021).

Dairy beverages are considered a very suitable food base for adding postbiotics as they are naturally rich in nutrients, that can help the microbes to grow and support fermentation process. Milk has proteins, lactose, vitamins, and minerals, which help microbes grow well and produce useful compounds during fermentation. In this way, different postbiotic compounds are formed in the product. In addition to their nutritional value, the dairy beverages also have sensory characteristics that are widely liked by the consumers. When postbiotic compounds are added to dairy beverages, there is also a possibility of beneficial interactions between the nutrients in milk and the metabolites formed during fermentation.

Although postbiotics have gained popularity recently, their application in dairy products is still relatively new and developing. Many things are still not fully clear, and there are still some gaps in the knowledge. In addition, there is still limited proof from human studies about their health benefits. Although several laboratory and experimental studies have shown encouraging results, more well-designed human studies are needed to clearly understand their health effects. Addressing these issues is important for supporting large-scale production and for developing clear regulatory guidelines for postbiotic-based functional foods. (Fijan, 2014)

Therefore, the present review study aims to examine the role of postbiotics in the dairy beverages in a clear and detailed way. The review explains the basic concept of postbiotics and discusses their functional and nutritional properties in detail. It also looks at the technological factors involved in producing postbiotics and adding them to dairy products. It also highlights the potential of postbiotic-enriched dairy drinks as innovative functional food products.

POSTBIOTICS: CONCEPT AND CHARACTERISTICS

The concept of postbiotics has recently received a lot of attention as a new type of functional component produced during microbial fermentation. Postbiotics are the products that contain non-living microbes, parts of these microbes, and useful compounds made during fermentation process that give health benefits to the body. Their effect does not depend on microbes staying alive during food processing, storage, or while passing through the digestive system. The composition of postbiotics is complex and can change based on many factors like the type of microbe used, the material used for fermentation, the processing conditions, and how the cells are made inactive. Postbiotics contain many useful compounds. Organic acids like lactic acid and acetic acid help control harmful microbes and affect gut pH. Bioactive peptides formed during protein breakdown can act as antioxidants, help control blood pressure, and support the immune system. Bacteriocins

act as natural substances that stop harmful microbes, while exopolysaccharides help control immune responses and can also affect the texture of foods. Fermentation produces short-chain fatty acids, which promote gut health and regulate metabolism. Enzymes, vitamins, and components of cells such as lipoteichoic acids, peptidoglycans, and surface proteins also contribute to their functions (Aguilar-Toala et al., 2021; Zolkiewicz et al., 2020; Cuevas-Gonzalez et al., 2020; Vallejo-Cordoba et al., 2020; Vinderola & Reinheimer, 2003)

One main feature that makes postbiotics different from probiotics is their better stability. Since postbiotics do not have living microbes, they are less affected by the temperature changes, oxygen, and acidity. Because of this, they can be used in many types of food products and under different processing conditions without losing their functional properties. In addition, the absence of live microorganisms can reduce safety concerns such as the risk of infection or the transfer of genetic material. Postbiotics are therefore more appropriate, particularly for the sensitive populations. (Zolkiewicz et al., 2020; Champagne et al., 2011)

As postbiotics can withstand both heat and non-heat processing techniques, they are technologically simple to incorporate into the food formulations. Additionally, their antioxidant and antibacterial qualities may increase the product stability and prolong the shelf life. These features make postbiotics a promising functional ingredient for use in different food systems, particularly in dairy beverages, where compounds formed during fermentation can interact with the nutrients naturally present in milk.

METHODOLOGY

Table 1. Key studies related to postbiotics and their applications in dairy systems

Author(s) & Year	Journal / Source	Focus Area	Microbial / Compound Focus	Key Findings	Relevance to Dairy Beverages
Aguilar-Toala et al. (2018)	*Trends in Food Science & Technology*	Concepts and definition	General postbiotics (LAB-derived metabolites)	Postbiotics as non-viable microbial products with functional benefits	Provides theoretical foundation for using postbiotics in dairy formulations
Aguilar-Toala et al. (2019)	*Current Opinion in Food Science*	Dairy applications	Fermented dairy postbiotics	Highlighted the potential of postbiotics in improving safety, shelf life and functionality	Supports incorporation into fermented dairy beverages
Salminen et al. (2021)	*Nature Reviews Gastroenterology & Hepatology*	Definition and classification	Microbial cells, metabolites, cell component	Standardized definition of the postbiotics	Provides the regulatory and scientific clarity for dairy applications
Rad et al. (2021)	*Journal of Food Science & Nutrition Research*	Functional properties	Peptides, SCFAs, bacteriocins	Antimicrobial, antioxidant, and immunomodulatory effects	Supports health benefits of the postbiotic dairy beverages
Cuevas-González et al. (2020)	*Food Research International*	Mechanism of Production	Lactic acid bacteria metabolites	Formation pathways and the technological production methods - explained	Helps to optimize fermentation in dairy systems
Moradi et al. (2020)	*Critical Reviews in Food Science and Nutrition*	Food safety and preservation	LAB-derived postbiotics	Role of inhibiting pathogens and improving the food safety	Important for extending the shelf life of the dairy beverages
Zolkiewicz et al. (2020)	*Nutrients*	Probiotics comparison	Broad postbiotic compounds	Highlighted the stability and safety advantages over probiotics	Supports industrial processing and storage of the dairy beverages
Wegh et al. (2019)	*Nutrients*	Nutritional and immune effects	SCFAs, microbial metabolites	Role in gut health and immune modulation	Strengthens the functional food positioning of dairy beverages
Plaza-Díaz et al. (2019)	*Advances in Nutrition*	Mechanism of actions	Bioactive metabolites	Interaction with gut microbiota and immune system - explained	Supports health claims in dairy-based products

Ranadheera et al. (2018)	*Journal of Functional Foods*	Dairy beverages	Fermented milk systems	Dairy beverages act as ideal carriers for functional ingredients	Direct relevance to the postbiotic-enriched dairy drinks
Linares et al. (2017)	*Foods*	Antimicrobial activity	Bacteriocins	Inhibition of spoilage and pathogenic microbes - demonstated	Supports natural preservation in the dairy products
Pescuma et al. (2015)	*International Journal of Food Microbiology*	Whey-based beverages	Fermentation metabolites	Highlighted- Whey as a substrate for functional beverage development	Supports sustainable dairy postbiotic production

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FUNCTIONAL AND NUTRITIONAL PROPERTIES OF POSTBIOTICS

Recent studies have shown that the postbiotics provide a wide range of functional and nutritional benefits that go beyond those commonly linked to probiotics.

Antimicrobial Properties

The antibacterial action of postbiotics is one of their most well-known characteristics. The pH of the environment can be lowered by organic acids like lactic acid, acetic acid and propionic acid, which prevents the growth of dangerous microbes. In addition to that, compounds such as bacteriocins and antimicrobial peptides can damage the cell membranes of the microbes, disturb their normal metabolic activities, and prevent the growth and spread the pathogenic microorganisms. Because of these actions, postbiotics can help to the maintain a healthier balance of the microorganisms in the gastrointestinal tract (Moradi et al., 2020; Linares et al., 2017).

Effects of Antioxidants

Numerous chronic illnesses, such as inflammatory and metabolic disorders, are significantly influenced by oxidative stress. Bioactive peptides, exopolysaccharides, and specific phenolic compounds produced during the fermentation are the key reasons why postbiotic preparations have demonstrated antioxidant activity. These substances can assist the body's natural antioxidant defence system, bind metal ions that encourage oxidation, and neutralise free radicals. Postbiotics may boost the metabolic health and protect the body cells by doing these things (Rad et al., 2021; Plaza-Diaz et al., 2019),

Modulation of Immunity

Another well-known feature of the postbiotics is their capacity of influencing the immune system. Immune cell receptors can interact with the structural elements such lipoteichoic acids, peptidoglycans, and surface proteins. Signalling pathways that can support a balanced immune response may be triggered by this interaction. Unlike live probiotics, Postbiotics can regulate the immune functions without the risk of microbial movement in the body or infection. Because of this, they may be more suitable for sensitive peoples. Research studies suggest that postbiotics may help strengthen the body’s natural immune defense, regulate cytokine production, and support the proper functioning of the adaptive immune system. (Wegh et al., 2019; Salminen et al., 2021; Taverniti & Guglielmetti, 2011)

Gut Barrier Integrity

To prevent the dangerous bacteria from entering the bloodstream from the gut and creating inflammation in the body, it is critical to maintain a robust intestinal barrier. It is well recognized that postbiotic metabolites, particularly the bioactive peptides and the short-chain fatty acids, might enhance the intestinal barrier function. They can support the formation of the tight junction proteins and help to regulate the immune responses in the intestinal lining. Because of these actions, postbiotics may help to reduce the intestinal permeability and maintain a healthy gut environment. In this way, they support proper digestive function and overall gastrointestinal health. (Plaza-Diaz et al., 2019; Wegh et al., 2019)

Mineral Bioavailability

The solubility and the absorption of minerals in the gastrointestinal tract can be enhanced by the organic acids generated during the fermentation process. By lowering intestinal pH and forming soluble mineral complexes, postbiotics may increase the availability of important nutrients including calcium, magnesium, and iron. Since these minerals are naturally found in dairy products, this characteristic can be especially helpful in it. The addition of postbiotics to dairy products may enhance the minerals absorption and also boost their nutritious content. (Aguilar-Toala et al., 2018)

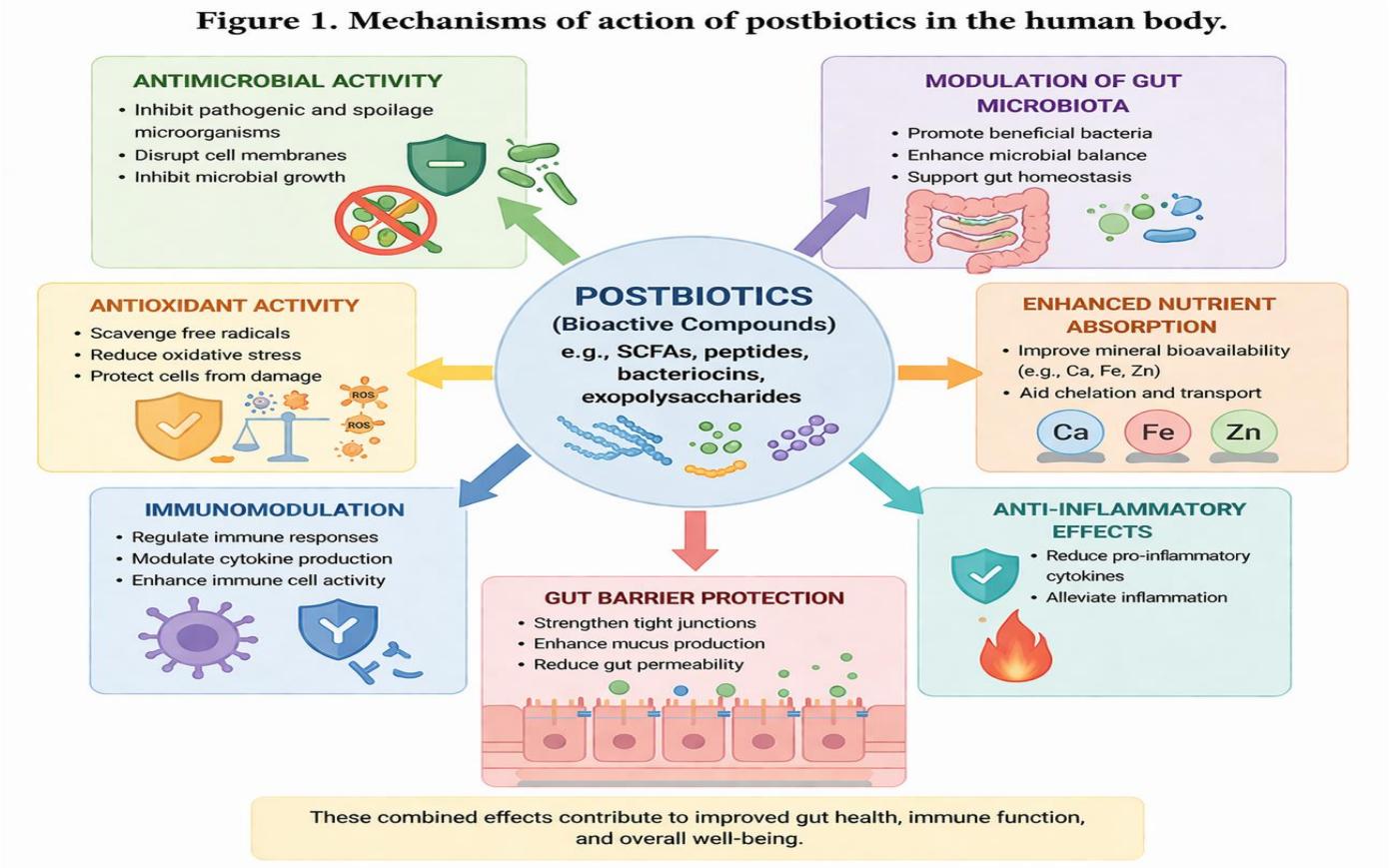
Anti-Inflammatory Potential

Long-term low-level inflammation is linked to the development of many metabolic and immune-related disorders. Several compounds found in postbiotics have shown the ability to reduce inflammation in the body. They can lower the production of pro-inflammatory cytokines and increase the activity of anti-inflammatory mediators. They may have an impact on the gut microbiota and interact with the immune signaling pathways to produce these effects. Because of these actions, postbiotics have good potential for use in the functional foods that support health. (Rad et al., 2021; Marco et al., 2021)

Enhanced Digestibility and Nutritional Quality

During fermentation, proteins are broken down into the smaller peptides and amino acids. The body can more easily absorb and digest these smaller molecules.Compounds resulting from fermentatio n may also reduce gastrointestinal distress and increase lactose intolerance. Therefore, the production of postbiotics during fermentation in dairy beverages can enhance the product's overall nutritional quality while preserving its flavor and texture. (Marco et al., 2017)

Figure 1. Mechanisms of action of postbiotics in the human body.



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POSTBIOTIC DELIVERY SYSTEMS: DAIRY BEVERAGES

One of the most excellent foods to add and supply functional bioactive chemicals, such postbiotics, is dairy beverages. Their natural nutrient content, buffering ability, and the good compatibility with microbial fermentation makes them suitable for the formation and stability of fermentation metabolites. Milk naturally contains high-quality proteins, lactose, important vitamins & minerals. These can support the microbial activity during fermentation and also help in the formation of different postbiotic compounds.

Milk proteins are act as substrates during the fermentation process. During this process, enzymes break down the protein and produce bioactive peptides that may show antioxidant, antimicrobial, and immune-supporting effects. At the same time, lactose in the milk is used by the lactic acid bacteria during the fermentation, leading to the production of organic acids and the short-chain fatty acids. These substances aid in both preserving the product and also promote the digestive health. Furthermore, the minerals found naturally in the dairy products contribute to the maintenance of the buffering capacity, which maintains stable fermentation conditions and promotes the appropriate synthesis of metabolites. Various dairy products have been investigated as postbiotic transporters. This shows that dairy systems are flexible and suitable for developing functional food products. (Shori, 2015)

Fermented dairy drinks

Fermented milk beverages provide a good environment for the formation of postbiotics through controlled microbial fermentation. In these products, useful bioactive compounds are produced during fermentation while pleasant taste and texture also develop. (Castro-Lopez et al., 2021)

Whey-based drinks

As a by-product of producing cheese and paneer, whey has developed into a significant and sustainable source for the postbiotic production. High protein and lactose contents can encourage microbial fermentation. This usage of whey promotes more sustainable food production systems and makes better use of the dairy byproducts.

Yogurt drinks

Drinkable yogurt products also provide a good base for delivering postbiotics because of their semi-liquid texture, high consumer acceptance, and compatibility with fermentation processes. Adding postbiotics to these beverages may further improve their functional properties and helps to maintain better stability during the storage.

Milk-based functional beverages

By adding postbiotics can improve the nutritional value of the beverage without affecting product safety or stability.

Cultured milk products and Kefir

A variety of bacteria that can produce a range of postbiotic metabolites can be found in the traditional fermented drinks like kefir. It is because of that multiple microorganisms coexist in these drinks; their interactions can broaden the variety of metabolites produced and also enhance the drinks functional advantages. Dairy products have a significant sensory benefit in addition to their nutritional value, which encourages the use of postbiotics. Fermentation produces compounds that enhance the mouthfeel, texture, and flavour of the product. These characteristics are crucial for the consumer approval. Most people are also familiar with the dairy products, which facilitates the market acceptance of postbiotic-enriched products. (Tamang et al., 2016)

The relationship between the postbiotic metabolites and nutrients in the dairy products is another important factor. Beneficial combination effects may result from these interactions. For example, milk proteins and peptides may interact with the microbial metabolites and help to improve their absorption in the body, while organic acids may increase the mineral absorption and support better digestion. These combined effects prove that the dairy products can function as multipurpose systems that offer both technological and nutritional advantages.

(Ranadheera et al., 2018; Pescuma et al., 2015; Aguilar-Toala et al., 2019)

TECHNOLOGICAL PERSPECTIVES - POSTBIOTIC DAIRY BEVERAGES

The introduction of the postbiotic enriched dairy products to the market is greatly aided by technological developments. Without worrying about keeping microbes alive, food technologists can more easily modify production conditions to enhance the creation of the beneficial metabolites, improve product stability, and also preserve good flavor and texture.

Techniques for Fermentation

The main method used to produce the postbiotics in dairy products is controlled fermentation. The selection of the microbial strains, such as bifidobacteria and lactic acid bacteria, plays a major role in deciding which metabolites are formed and how effective they are. The production of beneficial bioactive compounds like peptides, organic acids, and exopolysaccharides can be increased by carefully controlling factors such as temperature, pH, oxygen levels, and the type of substrate used. Recent developments in the metabolomics and precision fermentation have made it easier to identify and control the specific postbiotic compounds. This helps in developing the functional dairy beverages designed to provide specific health benefits. (Cuevas-Gonzalez et al., 2020; Moradi et al., 2020)

Microbial Inactivation Techniques

In this process, microorganisms must be inactivated to produce the postbiotics while keeping the beneficial substances safe and ensuring product safety. For this purpose, heat treatments such as pasteurisation and sterilisation are most used. New non-thermal methods like irradiation, pulsed electric fields, and high-pressure processing are also being studied. These methods help to inactivate the microorganisms without damaging the heat-sensitive compounds, thereby preserving their functional benefits. (Moradi et al., 2020)

Stability Advantages

One of the main advantages of postbiotics compared to probiotics is their higher stability. Since they do not contain live microorganisms, they are less affected by factors such as temperature changes, oxygen exposure, and acidity. This makes it easier to handle during processing and storage. As a result, products containing the postbiotics have a longer shelf life and also they are more suitable for large-scale production. (Zolkiewicz et al., 2020; Aguilar-Toala et al., 2019)

Shelf-Life Improvement

Postbiotic compounds, especially organic acids and bacteriocins, help to preserve the food naturally by preventing the growth of spoilage and harmful microorganisms This can reduce the need for artificial preservatives and support clean-label product development. In addition, antioxidant compounds formed during the fermentation process can slow down fat oxidation and help to maintain product quality for a longer period of storage. (Linares et al., 2017)

Sensory Optimization

Compounds formed during fermentation help improve the health value of the product, but they can also change the taste, sourness, thickness, and mouthfeel. So, it is important to keep a good balance between health benefits and taste. Methods like adding sweeteners, adjusting flavor, improving texture, and carefully controlling fermentation are used to make sure the product is tasty and acceptable to consumers.

Packaging Considerations

Good packaging is very important to keep postbiotics stable and effective. Packaging materials can prevent exposure to oxygen & light, that helps to protect the product from damage. Also, Aseptic packaging and proper cold storage methods can help to maintain product quality during transport and storage. (Champagne et al., 2011)

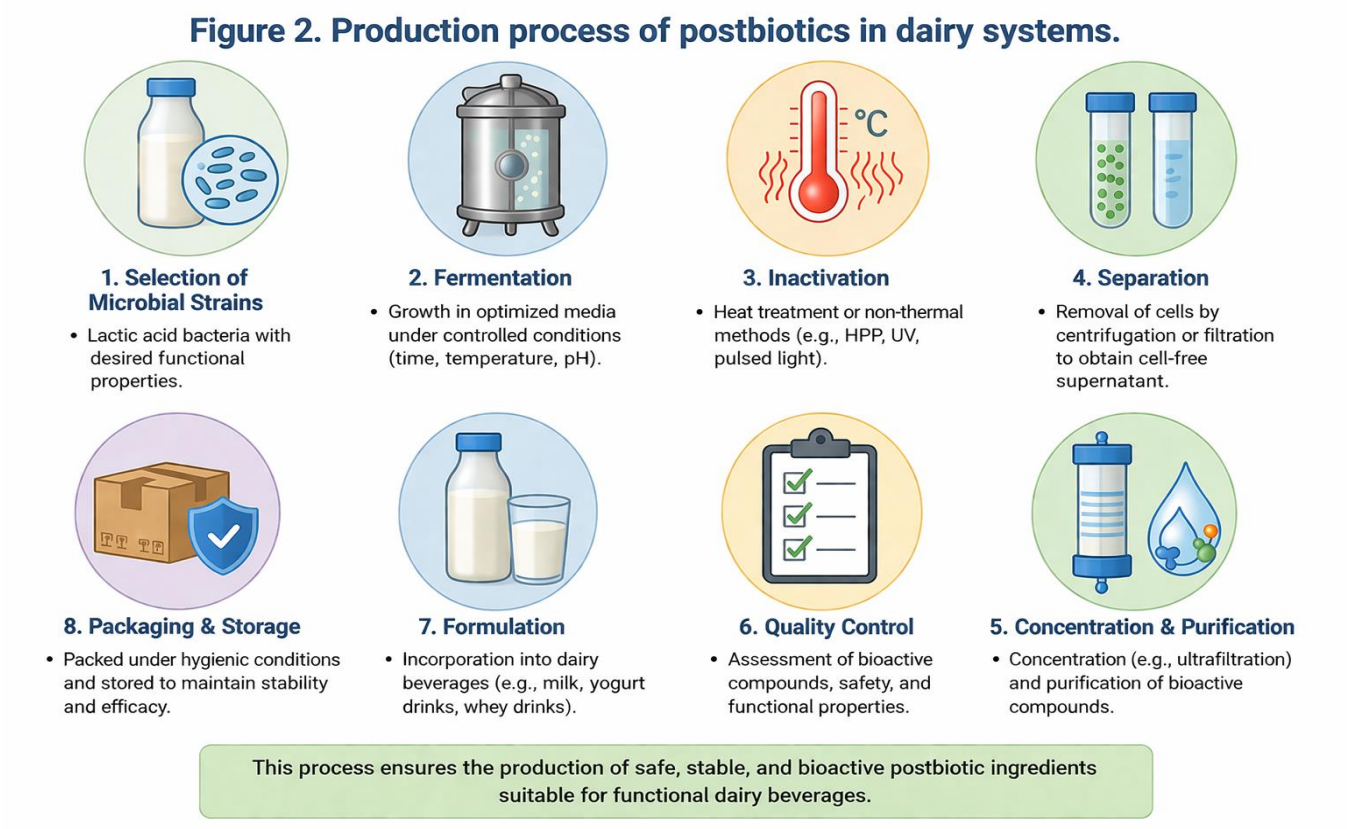
Safety Aspects

Postbiotic dairy products do not contain live microbes, which makes them safer than probiotic products. This reduces the risk of infections, movement of microbes in the body, and transfer of antibiotic resistance. These products are also less affected by contamination, which helps to keep the quality consistent and meet safety standards. Because of these properties, they are suitable for the sensitive groups such as infants, elderly people, and individuals with weaker immunity. (Fijan, 2014; Hill et al., 2014)

Future of Technological Innovation

Postbiotic dairy drinks is being made with the aid of new technologies such as improved fermentation, encapsulation, processing, and environmentally friendly materials. These techniques can employ the dairy waste, such as whey, to make drinks for various health needs and improve the way the beneficial compounds function in the body. When everything is considered, these advancements indicate that the postbiotic dairy drinks have a bright future as nutritious foods because they are more stable, safe, and also simple to prepare in many ways. (Moradi et al., 2020)

Figure 2. Production process of postbiotics in dairy systems.



Source: Created by author

COMPARISON OF STUDIES

Several studies have consistently reported that the postbiotics exhibit the wide range of beneficial effects, including antimicrobial, antioxidant and immunomodulatory properties (Aguilar-Toala et al., 2018; Rad et al., 2021). For example, Recent reviews highlight that postbiotics such as SCFA, peptides, and exopolysaccharides play a significant role in improving the gut health and immune function (Plaza-Diaz et al., 2019; Salminen et al., 2021).

Similarly, Other studies also focusing on the food applications indicate that postbiotics can enhance the safety and shelf life of the dairy products by inhibiting the pathogenic microbes and improving stability of the product. (Moradi et al., 2020; Aguilar-Toala et al., 2019).

In addition, multiple review papers emphasize that the postbiotics offer advantages over the probiotics due to their non-viable nature, which ensures that the better stability during processing and also storage while maintaining the biological activity (Zolkiewicz et al., 2020; Cuevas-Gonzalez et al., 2020).

However, comparative studies also suggest that the effectiveness of the postbiotics depends on several factors such as microbial strain, fermentation conditions and the type of metabolites produced (Aguilar-Toala et al., 2019). This indicates that not all the postbiotics exhibit the same level of functionality.

CONTRADICTIONS IN LITERATURE

Despite the promising findings, there are some contradictions reported in the literatures. While several studies were suggest that the postbiotics can provide the similar or even superior health benefits compared to the probiotics, other studies indicate that their effects may not always be equivalent (Zolkiewicz et al., 2020; Salminen et al., 2021). Some reports classify that postbiotics into the groups where they may be less effective, equally effective, or more effective than the probiotics depending on the condition studied (Rad et al., 2021).

Additionally, although the postbiotics are safe due to the absence of the live microbes, some studies highlight that the excessive or uncontrolled metabolic production may interfere with the physiological processes, suggesting that the need for controlled dosage and proper formulation (Moradi et al., 2020).

There is also an inconsistency regarding their clinical effectiveness, as many studies are based on only the in vitro or animal models, while human clinical evidence remains limited and also sometimes inconclusive (Salminen et al., 2021; Cuevas-Gonzalez et al., 2020).

RESEARCH GAPS AND FUTURE PERSPECTIVES

Several research gaps have been identified in recent studies (Wegh et al., 2019; Salminen et al., 2021; Moradi et al., 2020; Vallejo-Córdoba et al., 2020; Pescuma et al., 2015). One of the primary limitations involves the scarcity of well-designed clinical studies evaluating the health benefits of postbiotic-enriched dairy beverages. While in vitro and animal studies have demonstrated antimicrobial, antioxidant, and immunomodulatory effects, translation of these findings into human clinical outcomes remains limited. The absence of robust clinical evidence restricts the substantiation of health claims and may hinder consumer trust and regulatory approval.

Another important problem is that the exact composition of the postbiotics is not fully known. Postbiotics contain many compounds formed during the fermentation process, and their composition can change based on the type of microbes used, fermentation conditions, and also other processing methods. This variation makes it difficult to keep products consistent. Therefore, advanced methods like metabolomics and proteomics are needed to clearly identify these compounds and understand how they work in the body.

Although postbiotics have attracted growing attention as promising functional ingredients, their application in the dairy beverages remains at an early stage of development. Several scientific, technological, and regulatory challenges must be addressed to facilitate large-scale commercialization and support evidence-based functional claims.

Standardizing production is also a challenge. Differences in fermentation methods, ways of inactivating microbes, and formulation can affect how much of the metabolites are produced, how effective they are, and even the taste and texture of the product. Because of this, proper production guidelines and quality control systems needed to maintain consistent product quality.

Sustainability considerations provide an important avenue for the future investigation. The utilization of the dairy by-products such as whey as substrates for the postbiotic production offers opportunities for valorisation and also for circular economy implementation. However, optimization of fermentation processes and techno-economic feasibility assessments are required to support sustainable industrial adoption.

In the future, these studies should focus on combining different areas such as metabolomics, human studies, sensory studies, and better processing methods. New approaches like precision fermentation and the systems of biology can help to produce the specific metabolites and develop products for specific health needs. In addition, techniques like encapsulation and advanced delivery systems can also help to improve stability and effectiveness.

CONCLUSION

Dairy beverages - quality, nutrition, and processing all can be enhanced by postbiotics. They are stable, safe, and do not need live microbes, which makes them better than probiotics in many ways. Because of this, they are easier to use in processing and also help the product stay fresh for a longer time. Studies show that postbiotics can help fight harmful germs, act as antioxidants, support the immune system, and protect gut health. These benefits make them useful for making healthy foods.

Because dairy products are high in nutrient content, support fermentation process, and have become widely consumed, they are an excellent option for incorporating postbiotics. Postbiotics can now be added to the dairy drinks more easily without altering their flavour, texture, or quality because of their advancements in the fermentation, microbial inactivation, and product manufacturing.

But some issues still exist, there are not enough human studies to fully prove their health benefits, the exact compounds are not fully known, production methods are not standard, and also rules are not clear. Solving these problems through more research is important for the large-scale production and for making proper health claims. Overall, postbiotic dairy beverages have strong potential as the next-generation functional foods that can meet changing consumer needs and support innovation, sustainability and better public health.
(Aguilar-Toala et al., 2019; Moradi et al., 2020)

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