Chapter

Lactic Acid Bacteria: Review on the Potential Delivery System as an Effective Probiotic

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Abstract

Lactic acid bacteria are gram-positive microorganisms that are characterized by the production of lactic acid as a key fermentation product. LAB, specifically *Lactobacillus delbrueckii* subsp. *bulgaricus*, are essential dairy starter cultures for the manufacture of several fermented dairy products such as yogurt. Some LAB are useful microorganisms and are well known to have probiotic effects to provide foods with unique sensory qualities such as aroma and taste. Probiotic strains help to strengthen the human immune system, increasing the body's resistance to diseases. Additionally, probiotics and postbiotics improve gut microbiome balance and prevent health issues. Postbiotics are substances that are produced by microbes' metabolic activities and have a positive impact on diseases, either directly or indirectly. Extensive research has shown that postbiotics possess immunomodulatory and significant clinical effects. Their use has been found to enhance general health and alleviate symptoms of various disorders in healthy individuals. Furthermore, postbiotics exhibit anti-inflammatory, antioxidant, and anticancer properties. Therefore, this chapter presents an overview and the importance of LAB as a probiotic and its importance to human health, metabolic fermentation, and antioxidant potential. The review also discusses different biotechnological methods that improve the survival rate of probiotics during processing and GIT transit like microbial encapsulation.

Keywords: lactic acid bacteria (LAB), probiotics, lactobacillus, postbiotics, bifidobacteria, delivery system, microorganisms

1. Introduction

Lactic acid bacteria (LAB) are significant microorganisms that primarily generate lactic acid as a byproduct of metabolic processes. In the agricultural, pharmaceutical, food, and medical industries, lactic acid bacteria serve a wide range of purposes. One of the most common methods of preserving and prolonging the shelf life of food is the use of LAB, which is used in many food fermentations [1]. Lactobacillus is a gram-positive, rod-shaped bacteria commonly found in fermented foods that are beneficial for human health [2]. *L. bulgaricus* is among the most significant LAB, as it is recognized as one of the two bacteria needed for yogurt production. *L. bulgaricus* was isolated from Bulgarian yogurt, and today, the yogurt manufacturing industries use it in addition to *Streptococcus thermophilus* for fermentation. This LAB (*L. bulgaricus*) plays a significant role during yogurt production regarding organoleptic, hygienic, and perhaps probiotic characteristics; as a result, it is a safe probiotic with several advantageous qualities [1]. According to the FAO/WHO [3], probiotics are "live microorganisms which when administered in adequate amounts confer a health benefit on the host." These organisms are commonly found in foods such as yogurt, kefir, and sauerkraut, as well as in dietary supplements. Mani-López et al. [4] reported that the food sector, especially the dairy industry, is looking to enhance its knowledge of different probiotic bacteria to produce products that offer health benefits at a reasonable cost. However, the development of starter cultures for fermented dairy products depends on the microbial symbiosis of several lactic acid bacteria with excellent fermentation abilities [5]. Research confirms that commercial yogurt starter cultures' most significant fermentation properties include rapid acidification, specific flavor compounds, weak post-acidification, and health benefits with minimal dietary needs [1].

One of the key challenges in using Lactobacillus as a probiotic is ensuring its safe and effective delivery. Therefore, various delivery systems have been developed for Lactobacillus, and these delivery systems protect the bacteria from extreme conditions such as temperature, processing, storage, and the ability to withstand stomach acids and bile salts to colonize and exert their beneficial effects [6]. The success of a delivery system depends on several factors, including the viability of the bacteria during production and storage, and the ability of the delivery system to protect the bacteria during transit through the digestive system [6]. Advances in technology and research have led to the development of more effective delivery systems for Lactobacillus, which can potentially improve human health in various ways. Therefore, in this review, we discuss lactic acid bacteria focusing on Lactobacillus and their beneficial effects on human health applications as well as their effective delivery system to withstand harsh conditions such as temperature, processing, and storage, to maintain their viability.

2. Lactobacillus

Lactobacilli are fastidious lactic acid bacteria (LAB) of the family Lactobacillaceae that are mostly utilized in the dairy industries due to their fermentative properties. According to Ibrahim and Ouwehand [2], these microbes are non-spore-forming, aerotolerant anaerobes, which are rod-shaped, gram-positive, and part of the phylum Firmicutes, class Bacilli, and the order Lactobacillales. The aerotolerant property of Lactobacillus makes it possible for the organism to thrive in both anaerobic and aerobic environments. Lactobacilli are found to be part of the lactic LAB; therefore, they are usually distinguished based on their ability to create and produce lactic acid as a byproduct during glucose metabolism, which helps contribute to the preservation of the food due to the acid produced after the metabolism. They also contribute to individual sensory qualities such as flavor (aroma and taste) and texture and also enhance the organoleptic properties of foods [7], thus being classified to be the most important bacteria group amongst LAB in applied microbiology [8, 9]. Lactobacillus organisms play two key roles in the ecosystem, and these two distinct roles include being used as starter cultures in the dairy industries and being used as probiotic cultures. Lactobacillus species are usually used in the food industries (especially dairy industries) with other bacteria species such as streptococcus as a starter culture for fermentation during the manufacture of products such as yogurt, cheese, and sour milk. This is due to the ability of the lactobacillus to convert the sugar lactose into lactic acid to produce dairy products. Lactic acid is the major byproduct, which forms the larger percentage (at least 85%) of metabolic end products in numerous species, including *Lactobacillus acidophilus, Lactobacillus casei, and Lactobacillus plantarum*, indicating that glucose metabolism is primarily homofermentative. Many Lactobacillus strains are also isolated from different sources to be used as probiotic agents; however, it is unlikely that each species/strain possesses all the desired characteristics that will make it a suitable probiotic. Lactobacillus species are also used in the production of pickles and sauerkraut (fermented vegetables), wines and juices (beverages), and other products such as sourdough bread and sausages. The widespread utility of this microbe (Lactobacillus) is generally due to its Generally Recognized as Safe (GRAS) status, which makes a lot of people like its products. Lactobacilli are fastidious LAB and can be found in a variety of nutrient-rich environments such as dairy environments, microbial-rich host habitats such as human and other mammals' mucosal surfaces, and natural ecological niches such as decaying organic matter, soil, and insects' gastrointestinal (GI) system [2]. Also, Lactobacillus species are mostly found in various fermented foods, such as yogurt, as well as in nutritional supplements. Lactobacillu*s* can also be usually found in the crop and ileum flora of poultries, since these are good probiotics for the poultry thus promoting the growth of the bird and suppressing the growth of diseases causing bacteria in the poultry [8].

2.1 Taxonomic classification of lactobacillus

Lactobacillus was first classified by scientists based on its observable type of characteristics such as optimal growth and sugar utilization [10]. According to Ayivi et al. [1], new classifications of Lactobacillus have recently been approved by scientist due to the extent to which the new lactobacilli genera made it difficult to differentiate and categorize between the various lactobacilli species. These novel classifications are made of 25 genera, and this genus is of 262 species (as of March 2020), all of which are phenotypically, ecologically, and genotypically varied [10]. The reclassification comprises host-adapted species *L. delbrueckii* group and *Paralactobacillus* with the other 23 new species being *Amylolactobacillus, Apilactobacillus, Companilactobacillus, Lapidilactobacillus, Agrilactobacillus, Schleiferilactobacillus, Loigolactobacilus, Lacticaseibacillus, Latilactobacillus, Holzapfelia, Dellaglioa, Liquorilactobacillus, Ligilactobacillus, Lactiplantibacillus, Furfurilactobacillus, Bombilactobacillus, Paucilactobacillus, Limosilactobacillus, Fructilactobacillus, Acetilactobacillus, Levilactobacillus, Secundilactobacillus, and Lentilactobacillus*. This new classification represents the microorganism's evolutionary relationships, and environmental, biological, and metabolic properties [10].

2.2 Ecological niches of *Lactobacillus*

Lactobacillus species are among the most "sensitive" and fastidious microorganisms, which are usually located in nutrient-rich settings and other environments. These nutrient-rich habitats are classified as fermented/spoiled foods and animal feed, and the environment includes plant surfaces, soil, and the bodies of vertebrates, invertebrates, and humans [8]. Lactobacilli are the most common microorganism found in the microbiota of fermented foods. Lactobacillus is prominent in fermented foods such as cheese, yogurt, and milk (dairy products) because lactobacilli species are the primary bacteria employed in dairy fermentation. Lactobacillus has also been identified in fermented foods such as meats, veggies, and sourdough [8]. Due to that, the Lactobacillus species *L. plantarum* is the most common bacterial species that occurs naturally in vegetables like cabbage and lettuce [11]. Lactobacilli can also be found in the natural microbiota of the host animals, occupying numerous niches. They are healthy bacteria and therefore found in the human's gastrointestinal, urinary, and genital systems without causing any harm to the human body or producing disease [2]. They are also present in the mouth cavity and vaginal canal in humans forming part of the human microbiome and imparting great benefits to the human system such as the prevention of the growth of other harmful bacteria [12].

Lactobacillus can also be found in sewage and soils, where it causes fecal pollution. Soil samples have yielded isolates of *L. plantarum, Lactobacillus paracasei* subsp. *paracasei,* and *Lactobacillus brevis* species [13]. Lactobacillus has also been found and isolated in plants where sugar traces can encourage their growth.

2.3 Characterization of *Lactobacillus*

Lactobacillus is a LAB that is known for producing lactic acid as a byproduct of glucose metabolism. Considering the characteristics of microorganisms, Lactobacillus is perhaps the most important LAB being utilized widely in the food industries as starter cultures to perform key responsibilities such as the production of fermented foods and their possible probiotic effects on humans [14]. These LAB (Lactobacillus) cells have rod-shaped with a size in the range of $0.5–1.2 \times 10^{-10}$ μm; however, under certain growth conditions, the cells assume a coccoid-like shape [15]. Lactobacilli are auxotrophic and therefore grow best in nutrient-rich media, with the best growth temperature being 30–40°C; however, they can survive in a range of 5–53°C. The best (optimum) growth pH range for these LAB is 5.5–5.8 but can also grow at a pH < 5 [15]. The survival and viability of probiotic bacteria in adequate amounts in a product are the most significant requirements when considering the characteristics of probiotic strains in food. These Lactobacillus probiotic strains are not deficient in these characteristics and therefore make them a very good strain for the food industries. The characteristics of Lactobacillus that make them suitable probiotic microbe for use in the food industry include their resistance to bile and acid, adherence to human epithelial cells, colonization of the human intestine, production of antimicrobial substances, favorable growth characteristics, and favorable effects on human health. All these "rich" characteristics make it ideal for the effective utilization of the Lactobacillus strain in industries [16].

3. Health benefits of lactobacillus

Lactobacilli are useful probiotics that have a wide range of benefits ranging from health, industries (both pharmaceuticals and food), and fermentation of food substances to induce good sensorial properties such as flavor, texture, and increase the shelf life of the food (preservation). These LABs also form part of the human microbiota and induce a good effect on the human body system preventing the proliferation of other harmful and pathogenic microorganisms. Lactobacillus, for example, can aid in the digestion of food, the absorption of nutrients, and the fight against disease-causing microbes. For that reason, lactobacillus is said to be the most frequent bacteria used to treat diarrhea, including viral diarrhea and diarrhea caused by medications. Lactobacillus is also used to treat general digestive issues, newborn colic, and a variety of other stomach and intestinal ailments. Discussed below are some health benefits of Lactobacillus.

3.1 Protection of vaginal ecosystem

Microorganisms such as bacterial species have been shown to invade and create complex communities, or microbiota, in various human body parts (**Figure 1**). These microorganisms being present in the human microbiome appear to have a crucial role in the human body such as development, physiology, immunity, and nutrition [18]. The vulvar cleft in humans (females) connects the uterine cavity, endocervix, and vagina to the outside. These canals aid blood flow during menstruation, but they are frequently inhabited by a diverse mix of indigenous microbial flora. Lactobacillus species have long been recognized to exist in the vaginal canal of humans and serve a significant and perform essential role in maintaining and improving health by limiting the proliferation of harmful organisms by creating various defensive mechanisms [19]. Lactobacillus can provide these important health benefits to the individual by producing lactic acid, bacteriocins, and hydrogen peroxide, all of which limit the growth of bacteria, being harmful or not and fungal pathogens that cause urogenital tract infections [20]. This argument of Lactobacillus being present in a female's vagina canal to improve health agrees with the fact that Döderlein isolated Döderlein's

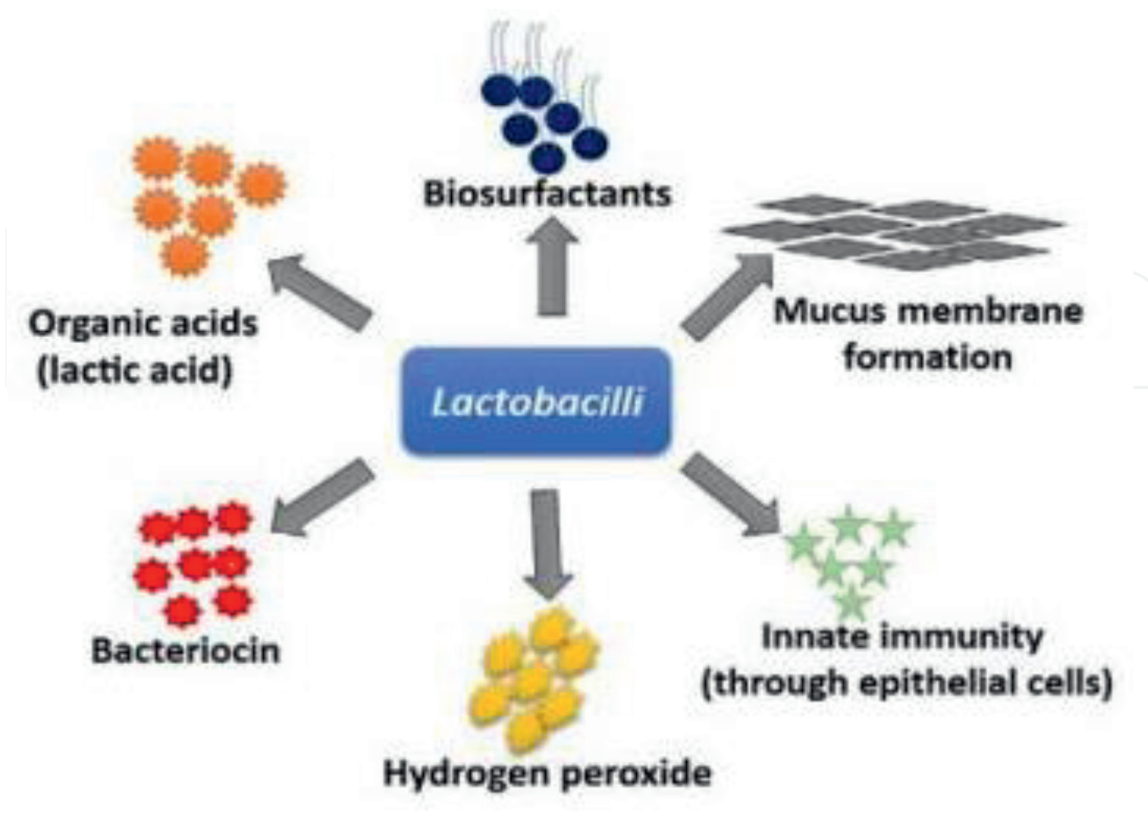

Figure 1.
Action mechanism of vaginal lactobacillus species [17].

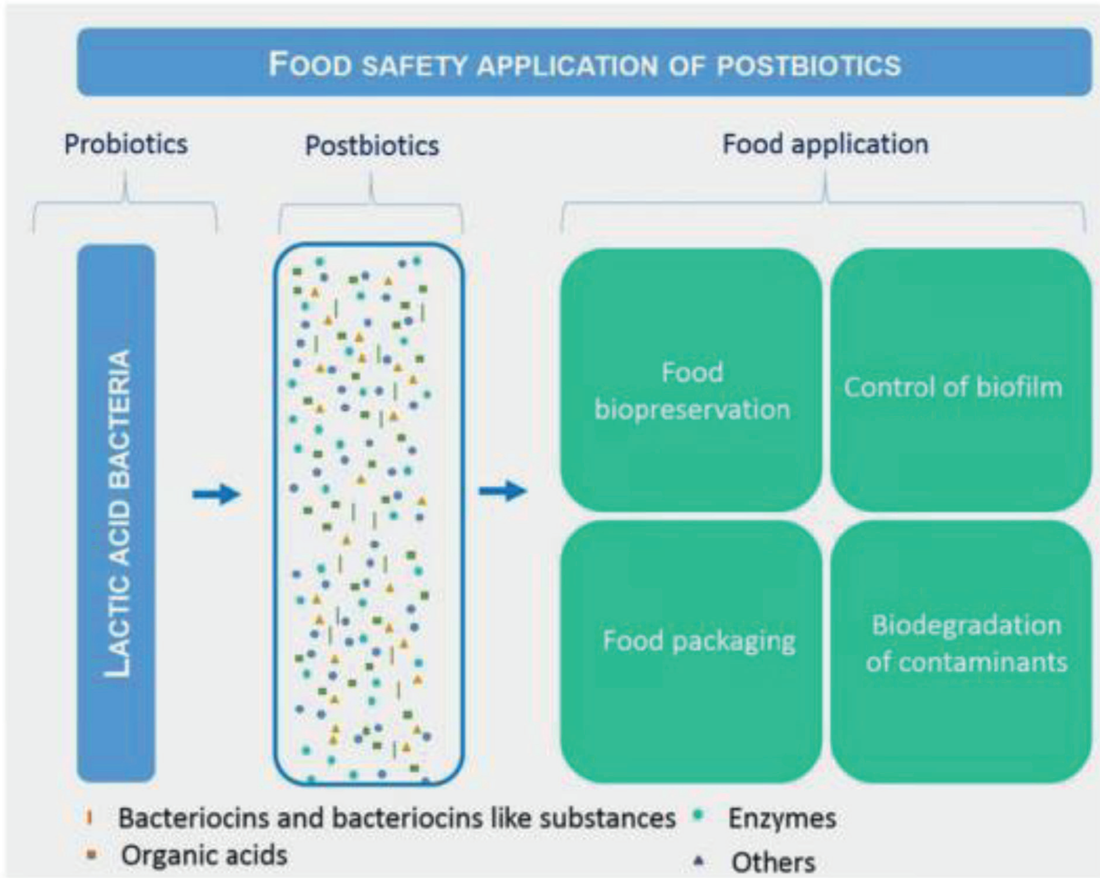

Figure 2.
The potential applications of postbiotics in food commodities [22].

bacillus from a healthy pregnant lady's vaginal samples and called it Lactobacillus [21]. It is generally known that the Lactobacillus being present in large quantity in the female genital organ's canal is "healthy" or "normal," and this is attributed to the vagina's excellent defense mechanism against other harmful bacteria, whereas a low or absent amount is deemed "abnormal" [17]. Lactobacillus species produce lactic acid as a product of glycogen digestion in follicular cells of the vaginal epithelium, resulting in an acidic environment (pH 4.5) [21]. A healthy vagina's acidic environment is an essential defense mechanism against the multiplication and growth of many potential diseases and infections [17]. Inhibitory substances produced by Lactobacillus to protect the vagina are shown in **Figure 2**.

The vaginal Lactobacillus functions by releasing substances that include lactic acid, bacteriocins, hydrogen peroxide, and biosurfactants to prevent the proliferation of harmful microorganisms and regulate the immune cells [17].

4. Carbohydrate metabolism of lactobacillus

The first and most essential step in food fermentation is the breakdown (catabolism) of carbohydrates by LAB. LAB as a group has a tremendous ability to break down carbohydrates and related substances. Lactic acid (>50% sugar carbon) is the primary product. It should, however, be noted that LAB adapts to different environments and adjusts their metabolism accordingly. This could result in dramatically different final product patterns [23].

4.1 fermentation of glucose

Fermentation of glucose with LAB occurs in two pathways which include either the pentose phosphate pathway or the Embden–Meyerhof–Parnas (glycolysis) pathway. These two major pathways are used to phosphorylate and metabolize glucose sugar [24]. Except for *Leuconostocs*, the obligately heterofermentative Lactobacilli, *Gonococci,* and *Weissellas,* the Embden–Meyerhof–Parnas pathway is found in all LAB. In this process, 1 mole of glucose produces 2 moles of lactic acid and results in a net gain of two ATPs [23]. According to de Oliveira [25], glycolysis can result in heterotactic fermentation under certain conditions, and some homofermentative LAB utilizes the pentose phosphate pathway to metabolize substrates. The phosphoketolase split of xylulose-5-phosphate to glycerol aldehyde-3-phosphate (GAP) and acetyl-phosphate is regarded as an essential and important step in the pentose phosphate pathway. After that, GAP is converted to lactate, and acetyl-phosphate is also metabolized to acetate and ethanol [24]. In sourdough fermentations, Lactobacilli are largely heterofermentative and use the pentose phosphate pathway to break down glucose. Oxygen and fructose may both be used as electron acceptors in microaerophilic circumstances, resulting in the creation of other metabolites such as acetate and mannitol [23].

4.2 Fermentation of fructose

Fructose, a hexose sugar abundant in many plants, is one of the most important monosaccharides for bacterial growth in most plant-associated habitats, and it is usually fermented by the two Lactobacilli metabolic pathways [26]. *Lactobacillus sanfranciscensis* and *Lactobacillus pontis* can thus use fructose as a carbon source; nonetheless, when maltose is present, they utilize it most as an electron acceptor to create mannitol [27], especially when oxygen is limited [27]. The acetate kinase process generates additional ATP during the conversion of fructose to mannitol, resulting in a shorter lag phase with a greater growth rate and biomass production. The predominant product, acetic acid, has a molar ratio of 4:1 (fructose: maltose) [27]. Fructose is converted to mannitol by *L. sanfranciscensis,* but a little amount of lactic acid and ethanol are produced by *L. pontis* [28].

4.3 Fermentation of lactose

Lactose is mostly regarded as the major carbohydrate in dairy products, and it is the only carbohydrate that is usually used by Lactobacilli for the rapid growth, development, and production of acid [7]. The utilization of lactose by Lactobacillus is usually determined by the system of transport and enzymes involved in the hydrolyzation of the lactose sugar. The Lactobacillus species transports the lactose sugar into the cell through the permease and after the transportation sugar is then hydrolyzed (broken down) into glucose and galactose by an enzyme known as β-galactosidase. As the result of lactose fermentation, the simple glucose and galactose are next metabolized using the Embden–Meyerhof pathway to release lactic acid. This lactose fermentation process can also use a pathway known as 6-phosphogluconate, and in this process lactic acid, CO_2, and ethanol are produced as the end product [29].

4.4 Fermentation of pentose

Pentoses like arabinose, ribose, and xylose, among other related carbohydrates, like gluconate, may all be broken down by several LABs. These compounds are processed through the phosphoketolase pathway after being taken in by cells through permeases [23, 24]. Pentose phosphate is then metabolized by epimerases or isomerases who phosphorylate the pentoses to create ribulose 5-phosphate or xylulose 5-phosphate [23].

4.5 Fermentation of disaccharides

Disaccharides are substances composed of two simple sugars (monosaccharides). LAB breaks down (metabolize) and splits disaccharides into simple sugars (two monosaccharides) for easy absorption into the bloodstream. Lactose, cellobiose, maltose, melibiose, sucrose, and other disaccharides are among those digested by LAB [24]. These sugars are transferred as free sugars or phosphorylated sugars passing through the cell membrane and then splitting into two monosaccharides or a monosaccharide and a monosaccharide phosphate [30]. Even though disaccharide fermentation appears to be more complicated than monosaccharide fermentation, some LABs prefer disaccharides as growth substrates; lactose fermentation by dairy LAB and maltose fermentation by sourdough LAB are two examples [24].

5. Lactobacillus as probiotics

5.1 History of probiotics

The term probiotic was taken from the Latin word (pro) and the Greek word (bios), both of which means "for life." The probiotics theory was introduced in the early twentieth century, according to Zoumpopoulou et al. [31]. A German chemist known as Werner Kollath came up with the term "active chemicals which are important and required for the healthy growth and development of life" in 1953 and that was when probiotics were first introduced. Probiotics were also defined by Lilly and Stillwell in 1965 as "substances released by an organism that boost the growth of another organism." In 1992, Fuller, on the other hand, also came up with a definition that "probiotics are live microbial feed additive with great benefits to the host by enhancing gut microbial balance" [32]. All these concepts are linked to the belief that probiotics are beneficial to human health. Despite all the above definitions for probiotics, FAO/WHO in [3] described probiotics as "live microorganisms that, when administered in suitable proportions, impart a health benefit on the host," and this FAO/WHO definition for the term "probiotics" was the most generally accepted. However, the relationship of being beneficial to health was not overlooked in the FAO/WHO definition, implying that probiotics are extremely beneficial to human health.

The first food makers used bacteria and yeasts to ferment this milk into fermented dairy products, although they were unaware of the presence of these microorganisms [33]. Scientists such as Hippocrates and others considered fermented milk to be more than just a food product but also to have useful medicinal properties. This observation supported the fact that sour milk was, however, later prescribed for curing stomach and intestinal disorders [34]. Louis Pasteur found the microorganisms responsible for the fermentation of this milk and other fermented products in the early 1900s, whereas Eli Metchnikoff (Russian scientist) was also the first to discover the positive influence of these microbes on human health [35]. As a result, he proposed his longevity without aging theory and linked it to the Bulgarian bacillus discovered by Stamen Grigorov (Bulgarian physician), and later suggested that lactobacilli might help mitigate the putrefactive effects of gastrointestinal metabolism that contributed to illness and aging [35]. He also stated that toxins produced by bacterial putrefaction in the large intestine and released into the circulation are the cause of aging.

"According to Metchnikoff, the intestinal bacteria' need for food allows humans to develop techniques to change the flora in our bodies and replace harmful microorganisms with healthy ones." This then explains in detail the "probiotic concept." Lactobacilli are considered probiotics by Metchnikoff (as opposed to antibiotics, which are damaging to the host's life), and probiotics may improve health and delay aging. Metchnikoff is based on these scientific theories in the development and expansion of the French dairy industry. The Pasteur Institute's Henry Tissier also isolated bacteria (now known as *Bifidobacterium bifidum*) from the feces of healthy breastfed newborns and advised recommending it to babies with diarrhea [23].

5.2 Probiotic consumption

Probiotic consumption is critical since they provide numerous advantages to the body, particularly the gastrointestinal tract (GIT). The most essential issue, however, is how it is introduced into the biological system. In the late 1960s, some viable probiotic strains such as Lactobacillus (some species) and *B. bifidum* "group" were introduced as cultures into dairy products in Germany due to their ability to adhere to and adapt to intestinal walls, as well as their useful property of producing mildly acidified products such as yogurts [36]. Though these fermented milky products were popular in Germany and were known as mild yogurts or "bio-yogurts," an alternative product known as acidophilus milk was also popular in the United States at the time (s). The incorporation of these probiotic strains into these fermented milk products and other commodities results in a variety of ways of administration and consumption into the human system, including meals, mostly fermented, and pharmaceutical items, such as capsules or microencapsulated form. According to Salminen et al. [37], if probiotic bacteria are a specified part of a food, Functional Food Science in Europe (FUFOSE) defines it as "live constituents of a food that exert beneficial effects on health."

Probiotic foods are always in demand in the general market because people are beginning to recognize their value; these foods currently account for between 60 and 70 percent of the overall functional food industry. This causes the dairy food sector to expand its market niche since a continual increase in dairy-type probiotic foods is noticed; nevertheless, nondairy items including vegetables, fermented meats, and fruit juices also contribute to the same amount of probiotic food products. Currently, there is no evidence that a high number of probiotics are harmful to human health; in some situations, they may even be quite useful and provide significant advantages to human health [38].

5.3 Origin and sources of probiotics

Probiotic bacteria have been discovered and isolated in a wide range of environments, including foods (fermented foods), animals, plants, and humans. These probiotics are found in these various sources for a variety of reasons, including their fermentative and preservation impact (mainly in foods), contribution to good health in the human ecosystem (in humans), and so on. According to Ayivi et al. [1], the Lactobacillus and the Bifidobacterium species are the most frequently used probiotics. These two LAB strains have been identified to dominate the human intestinal wall due to their high adhesion capacity and are also generally considered safe for use (GRAS). According to Quigley [39], these safe Lactobacillus strains are well suited for gastrointestinal supplementation because Bifidobacterium is a prominent constituent as far as the large intestine is concerned, whereas Lactobacillus also being a major inhabitant of the small intestine. Streptococcus thermophilus, nonpathogenic strains of *Escherichia coli, Enterococcus, Bacillus,* and yeasts such as *S. boulardii* are also bacteria strains that are as good as these lactobacilli and *Bifidobacterium* [1]. Together with other probiotics, some strains particularly *E. coli* provide health benefits such as efficiently treating constipation and other related gastrointestinal diseases [40].

One of the most common sources of these probiotics is yogurt, which contains diverse bacterial strains such as *L. bulgaricus* and *S. thermophilus*. Yogurts are frequently fortified with strains that have favorable health effects on the human system when consumed. *S. thermophilus* has probiotic qualities, according to Pieniz et al. [41], and thus, its fortification in yogurt products is highly important to induce health advantages to the body. The strains utilized, on the other hand, are chosen based on their ability to survive in the product throughout its shelf life as well as during their transit to the stomach and the rest of the GI tract, allowing them to reach the distal tract, where they largely exercise their function.

5.4 Probiotics and human health

Probiotics are usually linked to several health benefits, with most studies concentrating on the gastrointestinal (GI) tract but also showing promise in other regions of the body such as the respiratory system, vaginal tract, and subcutaneous tissue [42]. These advantageous characteristics vary depending on the strain, and while different attributes may be linked to a particular strain, numerous activities are frequently carried out through microbe interaction, either with one another or with the host [43]. They produce chemicals (antimicrobial substances) such as bacteriocins, which are naturally occurring antimicrobial substances that are typical of a proteinaceous nature with a lipid or carbohydrate moiety, or organic acids (specifically lactic and acetic acids, hydrogen peroxide, and so on) that lower the pH of the system during their colonization as well as other activities such as growth and metabolism [44]. These natural antimicrobials help to suppress infections. They can improve epithelial and tissue integrity and functionality during their stay in the gut, primarily by producing low levels of nitric oxide (NO), increasing mucus production, improving gut epithelial cell proliferation, inhibiting carcinogenic substance production or elimination through detoxification, and producing nutrients, particularly short fatty acids and vitamins [45]. Many different Lactobacilli and Bifidobacterium strains are presently available for use by humans in the inhibition and treatment of gastrointestinal (GI) infections [46]. Probiotics can promote intestinal health by regulating microbiota, stimulating and building the immune system, synthesizing and improving nutrient bioavailability, reducing symptoms of lactose intolerance, and lowering the risk of a variety of diseases [1]. During hydrolysis, several of these probiotics produce enzymes that have been demonstrated to improve protein and fat absorption. LAB, for instance, has been proven to boost vitamin B complex concentration in fermented foods [47]. Microorganisms acting in the digestive system or during the manufacture of cultured foods have been shown to increase the digestibility or absolute amounts of several dietary components, according to [47]. Probiotics offer a wide range of health and developmental benefits, some of which are discussed below. During fermentation, probiotics such as Lactobacillus can create enzymes such as lactase, which aid in the breakdown of lactose in dairy products. Lactose is a disaccharide that can induce intestinal distress in people with low levels of the intestinal enzyme lactase, resulting in bloating, gas, and abdominal pain [47]. Lactose intolerance is a genetic condition that affects around 75% of the world's population [48]. This condition limits the use of dairy products in a certain group of people. Lactobacillus, however, produces the enzyme known as lactase during fermentation, which hydrolyzes lactose into glucose and galactose for absorption. Kim and Gilliland discovered in 1983 that feeding lactose-intolerant individuals with fermented milk resulted in a significantly lower level of hydrogen in the breath when compared to individuals being fed with unfermented milk, and this low level of hydrogen indicates that lactose was metabolized before entering the large intestine.

Several probiotics have also been discovered to be added to the feed of animals to enhance the weight of these domestic animals. This weight gain was attributable to illness management and increased nutritional digestibility in the animals. Robinson and Thompson [49] conducted a study on humans and discovered that infants gained 21.9 oz. on average during their first month of life when fed a regular formula and 26.5 oz. when fed a special formula fortified with *L. acidophilus.* This research confirms that probiotics are useful in stimulating growth and development in young animals and individuals, according to evidence from different studies. By enhancing gut microbiota, restoring antioxidant systems, reducing insulin resistance and inflammation, and improving gut microbiota, probiotics also play a crucial role in the prevention of metabolic diseases including obesity, diabetes, and cardiovascular disease [50]. By competing with and sticking to the mucosal surface of the intestine and stimulating immunological responses, probiotics reduce intestinal infection and inhibit the development of Candida and *Helicobacter pylori* [51]. Some recommended microorganisms used as probiotics in both humans and animals and their health benefits are grouped in **Tables 1** and **2**, respectively.

5.5 Probiotics in cancer prevention

The gastrointestinal tract (GIT) of humans serves as a "storage" for the rich and diverse collection of microorganisms (gut microbiota), predominantly bacteria. Through homeostasis and illness throughout human life, this group of microorganisms generally has a significant impact on the host [63]. The human system has around 10 times more prokaryotic cells than eukaryotic ones because of the presence of gut bacteria. Lactobacillus, Bifidobacterium, Lactococcus, Streptococcus, and Enterococcus, as well as some *Bacillus* and *Saccharomyces* strains, are among the numerous microorganisms found in the GIT [64]. However, many of the products from probiotic products currently found in the market these days contain more LAB from the genera Lactobacillus and Bifidobacterium [65]. These beneficial probiotic microorganisms impart and play a variety of roles in the human system, including cancer prevention and treatment. Cancer is defined as a disease that emerges because of uncontrollable cell growth and spreads to other sections of the body. This killer sickness has been one of the human battle diseases that, if not treated properly, can usually lead to death. However, there has been a scientific basis and proof that

Lactobacillus	*Bifidobacterium*	*Streptococcus*	**Other bacteria**	**Yeast and molds**
acidophilus	*bifidum*	*lactis*	*Leuconostoc*	*Saccharomyces cerevisiae*
plantarum	*infantis*	*cremoris*	*Pediococcus*	*C. pintolopesii*
casei	*longum*	*alivarius subsp. thermophilus*	*Propionibacterium*	*A. niger*
rhamnose	*thermophilum*	*intermedius*	*Bacillus*	*A. Oryza*
delbrueck subsp. Bulgaricus	*adolescents*		*Enterococcus*	
GG	*animalis*		*E. faecium*	
reuter	*angulatum*			
fermentum	*pseudocantenulatum*			
brevis				
lactis				
cellobiosus				
johnsonii				
paracasei				

Table 1.
Microorganisms used as probiotics for humans and animals [50].

probiotic bacteria, such as the above-mentioned strains, usually prevents or minimizes the formation of some group of cancers in the human body, and this is because members of the gut microflora can create carcinogens such as nitrosamines [1]. Numerous studies have also shown the possibility of probiotics for the prevention and treatment of cancer. Most of these studies focused on the modulation of the microbiota, the immune system, the reduction of bacterial translocation, the improvement of gut barrier function, the anti-inflammatory and antipathogenic activity, and the effects of probiotics on tumor growth and metastasis [65]. Verhoeven et al. [66] discovered that regular intake of probiotics (drink) for about 6 months increased the clearance of HPV and cervical cancer precursors in 54 women. Another group of researchers discovered that probiotics or synbiotics significantly reduced the activity of intestinal procarcinogen enzymes linked to colonic carcinogenesis in experimental animal models [67]. All these findings from different research sources propose and portray probiotics to be a good source of cancer inhibition and reduction in the human system, thus making these useful microbes for consumption especially strains from the Lactobacillus and the Bifidobacterium genera.

Additionally, LAB may influence the maturation of immune cells and their products not only in the gut but also in systemic immunological organs like the lymph node and spleen, resulting in tumor inhibition [65]. These data suggest that probiotics could be useful dietary supplements against neoplastic susceptibility due to their wide influence on the host's local and systemic immune mechanisms [68].

Another encouraging research was published in 1980 by Goldin and Gorbach, who were among the first to correlate Lactobacillus-rich diets to a decreased risk of colon cancer (by 37 percent compared to controls). Many *in vitro* studies have also indicated

Probiotic strain	Health benefit	Reference
Lactobacillus rhamnosus GG	Prevention or alleviation of infantile diarrhea Prevention of early atopic disease in children at high risk	Salminen et al., [37], Szajewskah and Mrukowicz [52]
Bifidobacterium lactis HN019, L. rhamnosus HN001	Enhancement of natural immune function in healthy people	Arunachalam et al., [53]
E. coli Nissle 1917, S. boulardii, Lactobacilli, *Bifidobacterium*	Maintenance of remission of ulcerative colitis Treatment of Crohn's disease	Hart et al., [54], Marteau et al., [55]
Lactobacilli	Improvement of lactose digestion	Goldin [47]
Lactic Acid Bacteria	Reduces risk of bladder cancer	Ohashi et al. [56]
L. rhamnosus GG, Bifidobacterium species 420, L. acidophilus 145	Reduction of the occurrence of pathogenic bacteria in the nose	Gluck and Gebbers, [57]
L. casei strain Shirota, B. longum BB536	Reduces the severity of constipation and improvement of bowel movement and stool consistency. Increase defecation frequency and stool softness	Chen et al., [58]
Lactobacillus, Bifidobacterium	Treatment of *H. pylori* infection	Kuo et al., [59]
Enterococcus faecium, S. thermophilus	Decrease in LDL-cholesterol	Sanders and Marco, [60]
L. acidophilus NCFM	Minimizes risk of diabetes and obesity	Andreasen et al., [61] Sanchez et al., [62]

Table 2.
Probiotic bacteria and their health benefits.

probiotics' therapeutic properties in regulating the growth and death of cancer cells such as gastric, colonic, and myeloid leukemia cells [69]. Despite this, many researchers have discovered that the *L. rhamnosus GG* strain has a significant antiproliferative effect and/or induces apoptosis in mus musculus colon carcinoma (HGC-27) and human colonic cancer cells (Caco-2, DLD-1, and HT-29) [70] as well as lowering the level of IL-8 [71].

The ability of probiotics to prevent the growth of colon cancer (colorectal) may be attributed to several mechanisms, some of which include modification of the intestinal microflora, inactivation of cancer-causing agents, competition with putrefactive and pathogenic microbiota, improvement of the host's immune system, antiproliferative effects such as regulation of apoptosis and cell differentiation, fermentation of undigested food, and inhibition of tyrosine [72].

6. Lactobacillus as a starter culture for the dairy industry

Lactobacillus and other related species have been utilized as starter cultures for fermentation operations in a wide range of industries. Starter cultures are therefore regarded as an important component of basically fermented foods produced commercially, and nonetheless, these starter cultures are composed of useful microbes such as *Lactobacillus* which are directly introduced into the various food components, which help to produce the desired and predict the occurrence and characteristics in the finished product, which is the food [73].

Several fermented foods can indeed be produced without the need for a starter culture; however, adding a concentrated number of microorganisms such as *Lactobacillus* as a starter culture makes a difference and ensures that the food has desired characteristics such as the extension of shelf life, increased nutritional value benefits, altered sensory aspects, and an increase in economic value. According to Durso and Hutkins [73], several local methods for creating starter cultures for LAB involve backslopping or inoculating (introducing into) a fresh batch with a little quantity of the completed, particularly preserved product.

Other ways for starter culture production include harnessing microorganisms naturally found on the product and using specific containers that allow the starter culture microbes to survive within cracks and holes. These traditional fermentation procedures, however, allow for the creation of a variety and distinct fermented foods and drinks, and they are still utilized in small- to medium-scale manufacturing facilities, as well as in developing nations. These techniques of creating starter cultures, on the other hand, are prone to delay or failure fermentations, contamination, and variable product quality [73]. Following the discovery that pure cultures could be used to mature milk in the late 1880s by a team of scientists led by Storch of Denmark, Weigman of Germany, and Conn of the United States, the significance of flavor-producing bacteria (i.e., citrate-fermenting diacetyl-producers) was quickly established. Therefore, Christian Hansen established a starter culture business in 1978 based on this knowledge, and it has since grown to become a significant starter culture provider to industries such as brewing, dairy, baking, wine, and meat industries. In the past, producer-created starter culture strains were made by growing pure strains in heat-sterilized milk. These liquid cultures are still useful and well-liked today, despite having a short lifespan because of the loss of cell viability activities due to fermentation. Another technique of culture preparation, known as the crude dry culture preparation method, was devised; nevertheless, this method required multiple milk transfers to activate and respond to the culture. Freeze-dried cultures that were first produced in the 1960s are now noted to be one of the dairy cultures being used widely in the food industries. These cultures now dominate the starter culture industry because of the major advancements in freezing and freeze-drying methods. Given that starter culture bacteria's primary function is to ferment sugars and create acids, the capacity of LAB to metabolize carbohydrates is very essential.

7. Postbiotic

"Postbiotics" is known to be a new term in the biotic field, and therefore, they are still not common to the public. Therefore, in contrast to pre- and probiotics, it has, however, become more challenging to get a consensus on the true definition of postbiotics in the available literature. Nevertheless, Tsilingiri and Rescigno [74] defined postbiotics as any chemical released/created by the metabolic activity of a bacterium that directly or indirectly benefits the host. Postbiotics were also described by Blazheva et al. [6] as "a preparation of inanimate microbes and their constituents which is beneficial to the health of the host." Postbiotics are therefore functional bioactive substances that are created in a matrix during fermentation and are employed to support the health of individuals [6]. Several of the suggested health benefits of probiotic, prebiotic, and synbiotic additions depend on the possible production of short-chain fatty acids and components such as microbial fractions, functional proteins, secreted polysaccharides, extracellular polysaccharides, cell lysates, teichoic acid, peptidoglycan-derived muropeptides, and pili-type structures [75–77]. These understandings contributed to a reappreciation of food fermentation and gave rise to the theory of postbiotics. Postbiotics can also be described as functional fermentation chemicals, such as the ones mentioned above, that can be combined with dietary elements to enhance health [64]. Paraprobiotics and fermented infant formulas (FIFs) are two examples of postbiotics that are frequently mentioned. These days, the term "paraprobiotics," also known as "ghost probiotics," "non-viable probiotics," or "inactivated probiotics," is frequently used to refer to nonviable or inactivated microbial cells that, when provided in adequate proportions, benefit the host [64], whereas FIFs are baby or follow-on formulae that have been fermented with lactic acid-producing or other bacteria and often do not contain living bacteria [64]. The potential for postbiotics to boost the effectiveness of active microorganisms or transform them into useful components is possible. Additionally, postbiotics get around the technical difficulties of maximizing colonization and preserving the viability and stability of the microorganisms at high doses in the product. Postbiotics can also be employed in circumstances where it is more difficult to regulate and maintain the conditions for manufacture and storage, such as in underdeveloped nations [64]. Additionally, it has been suggested that using postbiotics in critically ill patients, young children, and premature newborns may be a desirable substitute for other "-biotics" [78]. Food, microbiology, and customized medicine may become even more intertwined according to the postbiotics idea [64].

In general, all substances created because of microbial fermentation might be "postbiotics." Additionally, the concept of these postbiotics is often established on the concept that these microbiotas release a variety of metabolites during/after fermentation, and these metabolites impact positive effects on the health of humans. In addition to treating various types of diarrheas, postbiotic consumption in healthy people has been shown to improve general health and alleviate the symptoms of a variety of illnesses, including atopic dermatitis in adults and colic in newborns. Numerous studies have shown that postbiotics can have clinically significant effects as well as immunomodulatory effects. In addition, postbiotics also have antioxidant, anti-inflammatory, and anticancer capabilities [79]. Postbiotics have some significant functions, which include boosting active microorganisms to work more effectively or transforming them into useful components. This might perhaps speed up the transport of active substances to the intended location in the gut and extend the shelf life of these chemicals [80].

Postbiotics may also impart several benefits in food safety, and one of the advantages of adding probiotics to food is that they interact with pathogenic bacteria, which may inhibit pathogen growth by competing with them for resources such as nutrients or by secreting antimicrobial compounds [81]. Probiotic bacteria generate antimicrobial compounds known as postbiotics, which have the potential to play a significant role in food safety by preventing the development of pathogens in food and enhancing consumer health. Numerous bioactive metabolites, including organic acids, short-chain fatty acids, carbohydrates, antimicrobial peptides, enzymes, vitamins, cofactors, immune-signaling compounds, etc., are present in postbiotics made from LAB [82, 83]. In almost every study pertaining to food safety, the authors created a CFS solution that contained biological compounds produced by target bacteria and employed as postbiotics. Several LAB strains can be thought of as probiotics, and their postbiotic products frequently provide consumers with similar or complementary health benefits [84]. To enhance the technical qualities and lengthen the shelf life of foods, LAB has been widely employed, whether as the primary starter or as the secondary starter [22]. Postbiotics have several qualities that distinguish them from probiotics and make them important components. For instance, postbiotics have advantages over parent bacterial live cells in that they have a longer shelf life, safer structures, cannot spread antibiotic resistance, do not produce biogenic amines (BA), are simple to use and store, are stable in a wide range of pH and temperature, and have broad-spectrum antimicrobial activity [22, 85]. The difficulty in using live starter cultures directly in food products is ensuring that they will grow and survive in a variety of food matrices and settings. In this regard, the direct addition of a postbiotic mixture or individual postbiotic prevents unfavorable interactions between live primary and adjunct starters for antimicrobial purposes [86]; however, there are some challenges in the use of individual postbiotic of starters and protective cultures. Despite the high expense of bacteriocin separation and purification, antimicrobial metabolites have a restricted spectrum, making it possible for infections that have been treated with some of them, such as bacteriocins, to acquire resistance. In addition to a postbiotics mixture's excellent heat stability, food may fully benefit from its broad-spectrum antibacterial activity and the synergistic interactions between organic acids and other metabolites. Individual postbiotics perform a variety of well-known and newly discovered food safety roles, such as food biopreservation and packaging, control, and elimination of the biofilm of foodborne pathogens, biodegradation of dangerous chemical contaminants (such as mycotoxins, pesticides, and BAs), and much more. According to Moradi et al. [22], the kind of target microbe or pollutant, the concentration and method of administration, and the properties of the food matrix all affect how effective postbiotics are in food systems.

7.1 Antioxidants potential of probiotics and postbiotics

7.1.1 Probiotics

Antioxidants are chemicals that significantly slow down or stop an oxidizable substrate from oxidizing when present in a low amount as compared to the other substrate [87]. According to Blazheva et al. [6], oxidative stress is a pathological situation that occurs when reactive oxygen species (ROS) overtake the body's antioxidant defenses, causing tissue damage, accelerated cell death, and oxidative modification of biological macromolecules (such as lipids, proteins, and DNA). Oxidative stress is just a body-wide imbalance between free radicals and antioxidants. In this circumstance, reactive nitrogen species (RNS), which cause oxidative stress, and ROS are mostly captured by antioxidants [6]. Antioxidants act as scavengers of ROS and RNS, protecting living organisms from the damaging effects of oxidative stress; as a result, compounds having antioxidant activity are of special importance. Probiotic bacteria thus have special properties that can give antioxidant effects to humans, according to recent studies, and this helps to avoid disorders linked to oxidative stress. Additionally, probiotic bacteria influence the intestinal barrier's permeability and inhibit the overabundance of dangerous bacteria in the gut microbiota [6].

Bifidobacteria are one category of microorganisms that are often regarded as probiotics since they live naturally in the human GIT and have been linked to a healthy colon microbiota [6]. Because Bifidobacteria are strict anaerobes, the oxygen being present in the GIT acts as a stressor, causing it to create antioxidant molecules to scavenge these free oxygen radicals. Nonetheless, the amount of these antioxidants produced has not been reported in the literature [6]. Bifidobacteria can produce a variety of chemicals that can impede free radical oxidation processes and decrease oxidized molecules. These chemicals and other metabolites are known as the "post-biotics," and they help these probiotics in their specific actions. Some Bifidobacteria produce conjugated linoleic acid metabolites that exhibit the capacity to shield cells from damaging oxidative activity. Different species of Bifidobacteria have genomes that contain a gene for linoleic acid isomerase [88]. As byproducts of the fermentation of plant materials, Bifidobacteria are also capable of producing polyphenols, lignans, and flavonoids, all of which have an antioxidant impact and contribute to the probiotic function of the microbe [6]. A total of 25 Bifidobacterium strains were evaluated by Braune and Blaut [89] for their ability to produce lignan and flavonoid aglycones from flaxseed and soybean extracts. Most of these *Bifidobacterium* strains increased the levels of apigenin, daidzein, genistein, naringenin, and secoisolariciresinol. Additionally, the Bifidobacterium *pseudocantenulatum* and *Bifidobacterium* breve strains produced quercetin and quercetagetin, enhanced the quantity of kaempferol, and exhibited significant levels of herbaceous synthesis. The *Bifidobacterium* strains converted a wide variety of flavonoids' glycosides into their aglycones, boosting their antioxidant activity and bioavailability. According to Mayo and Van Sinderen [90], studies on the biosynthesis of vitamins by Bifidobacteria have revealed that *B. bifidum, B. breve, Bifidobacterium adolescentis, B. longum subsp. infantis,* and *B. longum subsp. longum* can all produce the vitamins nicotinate, thiamine (B_1), pyridoxine (B_6), and folate (B_{12}). Vitamin B_6 is a cofactor of glutathione and plays a significant part in the antioxidant process. Folic acid (B_9) also boosts the lipoproteins' resistance to oxidation [90].

The gut microbiome includes another useful microbe called *Lactobacillus* as well, and they both possess strong antioxidant properties. It has been demonstrated that some strains of lactobacilli, although being facultative anaerobes or microaerophilic, may use oxygen as a substrate in processes mediated by flavin oxidases and in specific circumstances can create a minimal respiratory chain. The production of several antioxidant proteins is the main factor affecting lactobacilli's antioxidant abilities. Very infrequently, lactobacilli produce the enzyme superoxide dismutase (SOD), which neutralizes superoxide anion [6]. Included in the antioxidant abilities of lactobacilli are the same proteins that control the chelation of iron and copper ions. Numerous antioxidant substances, including riboflavin, vitamin B_{12}, and carotenoids, are produced by different Lactobacillus strains. In addition, Lactobacilli shows antioxidant traits for the microorganisms they are symbionts for. The genes and proteins that protect lactobacilli from free radicals and their antioxidant qualities are well understood; however, little is known on the parts of lactobacilli cells and their metabolites that shield other microorganisms from free radicals. According to studies, certain strains of lactobacilli's culture fluid exhibit these characteristics in the form of exopolysaccharides, linoleic acid metabolites, histamine, vitamin K_2, and soluble proteins [6]. Because probiotic bacteria from the Lactobacillaceae and Bifidobacterium families have historically been used by people to ferment food, they are widely regarded as safe (GRAS). Additionally, probiotic bacteria in the human gut have significant antioxidant activity and encourage the synthesis of antioxidant enzymes to aid in the removal of reactive oxygen species and so lessen oxidative damage. To protect cells from oxidative stress-related damage, probiotic bacteria that build up in the GIT can boost the activity of antioxidant enzymes and reduce systemic circulatory oxidative stress. In addition to being utilized to treat early stages of disorders such as ulcerative colitis, irritable bowel syndrome, and allergic diseases, strains with antioxidant qualities can help the body's antioxidant status return [6].

7.1.2 Postbiotics

Research on the antioxidant properties of postbiotics has just become known. In an evaluation of the several postbiotic types of medications, Zólkiewicz et al. [79] investigated bacterial lysates, exopolysaccharides, enzymes, cell wall fragments, short-chain fatty acids, cell wall fragments, cell-free supernatants, and metabolites produced by the gut microbiota. According to Coelho et al. [13], *Liquorilactobacillus satsumensis, Leuconostoc mesenteroide,* and *S. cerevisiae* all have antioxidant activity that inhibited 2, 2-diphenyl-1-picrylhydrazyl (DPPH) by 20 to 28%.

Exopolysaccharide from *Lactococcus lactis subsp. lactis* has been studied *in vivo* as a postbiotics with reports of increased antioxidant enzyme levels (e.g., catalase, superoxide dismutase, and glutathione peroxidase activities) and decreased levels of lipid peroxidation in serum and mice livers [91]. Additionally, findings from *in vivo* studies support the same approach, showing that postbiotics have the capacity as an antioxidant and other health advantages. Postbiotics of lactic acid bacteria isolated from traditionally fermented sausages be potential agents of innovative pharmaceutical therapy for several illnesses associated with oxidative stress and are less dangerous alternatives to living microorganisms [6]. Studies have shown that the antioxidants of postbiotics vary and are influenced by factors that include the chelating ability of the metal ions, the antioxidant enzyme system, and the antioxidant metabolites present in them. As a result, postbiotics can be used as a treatment and feed supplements to minimize inflammation caused by disorders related to oxidative stress [6]. The above *in vivo* and *in vitro* studies provide crucial information regarding the ability of postbiotics to protect against oxidative stress, which is thought to be either a major or secondary cause of many cardiovascular illnesses, as well as to protect against damage caused by free radicals [92]. Postbiotics have also been studied for their potential antibacterial, antiviral, antioxidant, anti-obesity, anti-diabetes, antihypertensive, anti-proliferation, anti-mutation, and anticancer characteristics, and all these benefits have been shown *in vitro* and *in vivo* [93]. The most predominant benefits of postbiotics as natural antioxidants are generally their clinical (safety), technological (sustainability), and economical (low production costs) benefits [6].

8. Improvement of probiotic stability through biotechnological method

Probiotics must always maintain their viability and functionality during the process of production, storage, and ingestion to have their positive benefits. The manufacturing conditions (temperature, oxidation, shear stress, etc.), storage conditions (moisture/low water activity, packing, oxidation, temperature, etc.), and GIT conditions (low pH, bile salts, digestive enzymes) are the main principal factors that often impact these strains' capacity to survive. Encapsulation has been examined by several researchers as one of the direct methods for avoiding or lessening the impact of these factors. These probiotic bacteria are therefore delivered to their target places using this technology by establishing a microenvironment in which they can survive. Encapsulation is the process of shielding probiotics in particles to protect them from the environment by incorporating their microbial cells and/or their biologically active ingredients. To effectively perform its tasks, the capsules used for the encapsulation covering must be thin, semipermeable, and mechanically stable. By selecting a substance for the capsule that can create a "friendly" environment in the stomach and shield the probiotic strains from the stomach's acidic conditions and the bile salts secreted from the pancreas, however, it can also be made to release the probiotic cells in a specific location on the body [6]. Depending on the required features, which include polymers, several methods and materials were devised for the encapsulation of the probiotics. Considering the qualities, the encapsulation technique and the intended use of the finished product can help you choose the best shell or carrier material for this encapsulation. It must be suitable for industrial purposes, widely accessible, and simple to deal with. Polysaccharides of the plant including those from cellulose, pectin, gum arabic, agar-agar, alginate, carrageenan, inulin, and maltodextrin and those from animals (chitin, chitosan, hyaluronic acid, etc.) are the most often utilized encapsulating materials [6]. Probiotics are additionally encapsulated using resistant starch, oligosaccharides, as well as other fibers from fruits, vegetables, cereals, bran, and husk. Animal (casein, whey protein, and albumin) and plant (soy protein, pea protein, etc.) protein encapsulation ingredients are usually included in this category. However, their primary disadvantage is that digestive enzymes can degrade them, although this problem can be solved by coating them with another polymer [6].

8.1 Freeze drying

Freeze drying/lyophilization is a technique in which water is removed from a product after it has been frozen and put under a vacuum, allowing the ice to convert directly from solid to vapor without going through a liquid phase. Probiotic stability is stabilized by freeze-drying (lyophilization), which is typically done with cryoprotectants present and with the water being sublimated under a vacuum [6]. The purpose of the cryoprotectants is to increase microbial survivability and stabilize the product during storage. Probiotics' viability and shelf life are also enhanced by lyophilization, although this does not affect how long they survive in the digestive system. As a result, it is widely used as a second step in microencapsulation processing to increase the shelf life of probiotic bacteria by drying them out after they have been encapsulated in emulsions or gels [6]. Sugars like glucose, mannose, lactose, trehalose are among the most popular low-molecular-weight cryoprotectants. Most of the molecules with large molecular weight are polysaccharides and proteins, such as soy protein, milk, gelatin, and maltodextrin [94]. Wang et al. [95] coated sodium alginate microcapsules containing *L. plantarum* CCTCC M 2014170 cells with an inner layer of inulin and an exterior layer of skim milk before freeze-drying the mixtures. The findings demonstrated that the probiotic's resilience to the GIT's simulated environment was enhanced by encapsulation. In the stomach, *L. plantarum's* viability remained unchanged after 2 hours, but in the 1% bile salt solution, there was a 1.21 log drop in cfu/mL. The microencapsulation of probiotics *L. acidophilus* and *L. casei* by freeze drying was also studied by Bora et al. [96] utilizing whey protein isolate, fructo-oligosaccharides, with a combination at ratio (1: 1). In contrast to lose cells, which had a low survival rate after 90 minutes of incubation at pH 2, the probiotic that had been encapsulated had a high encapsulation yield (98%) and was not significantly impacted by the simulated stomach juice [96].

8.2 Spray drying

Another technique used in food processing is spray drying, which is employed for a variety of purposes including enhancing probiotic stability. Due to its suitability for large-scale industrial applications, affordability, and ease of scaling up, it is frequently utilized in the production of food products and bioactive chemicals [97]. When probiotics are dried using a spray technique, the liquid feed used for the encapsulating wall and the probiotics are both atomized into a hot gas drying chamber where the wet droplets are heated to a high temperature [6]. Emergence of dried solid particles is caused by the rapid creation of crusts. The primary disadvantage to this approach is the application of osmotic stress and high temperatures, which might result in reduced viability and loss of activity. After being sprayed-dried in feed solutions with varied amounts of gum arabic, the viability of *L. acidophilus NCDC 016* cells was examined in a study [98]. The input air temperature increase caused a drop in encapsulation yield, which was addressed by raising the gum arabic content. It was once believed that the proteins in gum arabic were what caused the microbial cell wall to produce a protective layer. *S. cerevisiae var. boulardii* was also encapsulated by Arslan et al. [99] spray drying temperatures. Gelatine and gum arabic were the most viable wall materials for *S. boulardii* microencapsulation based on viability tests following spray drying and subsequent tests under simulated gastrointestinal tract conditions.

8.3 Extrusion

Probiotic cells are also encapsulated through extrusion that involves the suspension of the bacteria in droplets of liquid which later gel or have membranes developed on their surfaces. Using coaxial air or liquid flow, submerged nozzles, vibration technologies for the jet break-up, and other methods, one can obtain the droplets pouring from a nozzle [6]. The droplets then enter a solution that will harden them. Particles of different sizes, morphologies, and mechanical strengths are created by varying the processes and materials used to produce gel beads. This technique of encapsulation is simple, affordable, and highly kind to microbial cells. However, its slowness restricts its use on an industrial scale. The targeted release potential of the gel beads was proven by the encapsulated *B. adolescentis* cells' log reduction values, which ranged from 2.0 to 2.6. In addition, the gel beads disintegrated when exposed to circumstances simulating intestinal juice. The probiotic *L. acidophilus KBL409* was encapsulated in alginate and alginate-chitosan, and then, all samples were incubated for 1 or 2 hours at 37°C with simulated stomach fluids (pH 1.5) before being exposed to simulated intestinal fluids (pH 6.5) for the next 2 hours. The largest percentage of survivors were found in the alginate/chitosan capsules [100]. To protect the microbial cells and extend shelf life, Apiwattanasiri et al. [101] suggest using silk sericin as a wall material and coating layer for probiotic encapsulation.

8.4 Emulsion-based system

Two immiscible liquids combine to produce an emulsion when an emulsifier (stabilizing agent) is present. The technique of creating an emulsion is simple and comprises the rapid mixing of the two phases (continuous and dispersed phases) while adding one phase over the other, which, if appropriate, also contains an emulsifier. Although it is easily scaled up, this process' primary limitation is that it generates particles of various sizes. Zhang et al. [102] developed secondary emulsions to contain *Ligilactobacillus salivarius.* The main emulsion was created by the emulsification of melted anhydrous milk fat with whey protein isolate or sodium caseinate in a neutral aqueous phase. This emulsion increased the encapsulation efficiency by up to 90% and improved the thermal and storage stability of *L. salivarius.* The probiotic survived the simulated gastric and intestinal digestions at a higher rate due to more cross-linking with calcium ions [102]. When *Lacticaseibacillus paracasei* was encapsulated in a milk-based water/oil emulsion, El Kadri et al. [103] found that the probiotic was more viable than free cells throughout 28 days of storage at 4°C, and this is due to the fact during storage the emulsion remained stable, and the encapsulated *L. paracasei* had a survival rate that was much greater than the free cells. To encapsulate the probiotic *L. casei* on an alginate matrix, flaxseed mucilage was employed. The encapsulation effectiveness was more than 95%, and stability and survival rates of the probiotic in simulated gastrointestinal conditions were evaluated [104]. As a result, *L. casei's* resistance to the negative effects of the simulated digestive system was strengthened by the introduction of flaxseed mucilage [104].

9. Conclusion

LAB, a class of widely distributed probiotic bacteria, plays a key role in the fermenting of different food products. LABs, specifically probiotics, have also been proven to impart a therapeutic effect on the remedy of several foodborne-related diseases. Thus, the role of these beneficial probiotics in fostering healthy microbiota and boosting resistance to illnesses and infections is crucial. Therefore, the importance of including probiotics in human diets cannot be overemphasized, given the numerous derived therapeutic health benefits. The survival rate of probiotics throughout processing, storage, and GIT transit has been improved by numerous authors using a variety of microbial encapsulation techniques. The gathered information demonstrates that these methods considerably boost the stability of various species and strains of probiotics. The effectiveness of such encapsulated microorganisms in the body must yet be evaluated through additional study. Even though the precise processes are still being completely understood, postbiotics may help to promote host health. For postbiotics to be shown to have a positive impact on health, well-designed randomized placebo-controlled intervention trials are required in addition to preclinical and *in vitro* research that focuses on the mechanisms of action. Additionally, a new era of "-biotic" research is beginning because of improvements in measuring the makeup and function of the gut microbiome. As a result, the variety of substances with potential health advantages that may be used in specialized nutrition has already increased and will continue to do so. Given that postbiotics face fewer difficulties in terms of storage and shelf life than viable probiotics, they can be a superb and secure way to improve health. Probiotics' potency may be effectively increased by postbiotics and bioactive substances, transforming them into useful components or medicinal agents. However, the nomenclature, regulatory considerations, and safety in use are the remaining postbiotics application-related issues that need further investigation by researchers to create global standards and regulations, which will then open new opportunities to produce healthier, safer, and more sustainable products [22].

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List of abbreviations

LAB	lactic acid bacteria
ROS	reactive oxygen species
RNS	reactive nitrogen species
GIT	gastrointestinal tract
FAO	Food and Agricultural Organization
WHO	World Health Organization
GRAS	generally recognized as safe
ATP	adenosine triphosphate
GAP	glycerol aldehyde-3-phosphate
GI	gastrointestinal
HPV	human papillomavirus
FIFs	fermented infant formulas

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