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Role of probiotics in the control of *Salmonella* infections in animals and humans

Ahsan Fayyaz [1], Jannat Fatima [2], Sara Mahmood [3], Yarfa Khurram [4], Gull Naz [5], Riffat Shamim Aslam [6], Ayesha Sarwar [5], Fatima Sarwar [6], Yusra Israr [7], Ayesha Israr [7], Afaq Ahmad [8], Abdul Rafay [8], Tehreem Shehzad* [9]

[1] *Department of Livestock and Poultry Production, Bahauddin Zakariya University, Multan, Pakistan*
[2] *Department of Pharmacy, The University of Lahore (UOL), Pakistan*
[3] *Department of Microbiology, Government College University Faisalabad, Pakistan*
[4] *Department of Pharmacy, Riphah International University, Islamabad, Pakistan*
[5] *Institute of Microbiology, Government College University Faisalabad, Pakistan*
[6] *Institute of Microbiology, University of Agriculture, Faisalabad, Pakistan*
[7] *Faculty of Veterinary Sciences, Bahauddin Zakariya University, Multan, Pakistan*
[8] *Faculty of Veterinary Science, University of Agriculture Faisalabad, Pakistan*
[9] *Department of Zoology, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan*

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* *Corresponding author:*
Tehreem Shehzad
Email: shehzadtehreem1122@gmail.com

Abstract

Salmonella infections pose a significant threat to human and animal health, leading to foodborne illnesses, economic losses in the livestock industry, and challenges in public health management. Various chemical drugs including antibiotics have been used to control *Salmonella* infections but overuse of these drugs has led to the emergence of multidrug-resistant strains, necessitating alternative strategies. Probiotics have emerged as the best alternative in controlling *Salmonella* infections because they promote gut health in both humans and animals. Probiotics are best because they are involved in enhancing modulation of gut microbiota, production of antimicrobial compounds, and immunity stimulant, thereby inhibiting *Salmonella* colonization and reducing infection severity. Different probiotic strains, especially *Lactobacillus* and *Bifidobacterium,* have shown efficacy in reducing *Salmonella* shedding and improving gut health in livestock, ultimately lowering zoonotic transmission risks. This review study explores the mechanisms by which probiotics combat *Salmonella*, and their various effects including antioxidant, immunomodulatory, anti-hypocholesterolemia, and anti-allergic. Understanding the role of probiotics in preventing and managing *Salmonella* infections can contribute to improving food safety, reducing antibiotic resistance, and enhancing animal and human health.

Reviewed by:

Muhammad Mohsin
Fujian University of Traditional Chinese Medicine, Fujian, Fuzhou, China
Asif Ali
Faculty of Veterinary and Animal Sciences, University of Layyah, Pakistan
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1. Introduction

Salmonella is a pathogenic bacteria that causes infections in both humans and animals, leading to significant public health and economic concerns (Ayuti et al. 2024). *Salmonella* is a rod-like, facultative anaerobic, non-sporulating, gram-negative bacteria. A peritrichous flagellum is used by *Salmonella* cells to migrate towards a favorable environment to get nutrients. This movement is known as chemotaxis, which helps Salmonella to colonize and infect host tissues efficiently (Malabadi et al. 2024). In addition to producing hydrogen sulfite and fermenting lactose (in some subspecies), *Salmonella* is both catalase-positive and oxidase-negative (Gut 2022). It is responsible for salmonellosis which is a common foodborne illness affecting millions each year globally. In humans, *Salmonella* infection primarily manifests as acute gastroenteritis while other signs and symptoms include fever, nausea, vomiting, abdominal cramps, dysphagia, and diarrhea (Herekar et al. 2022). The incubation period ranges from 4-72 hours after the consumption of contaminated food or water (Zheng et al. 2024). Certain serotypes, such as *S. typhi* and *S. paratyphi* cause enteric fever, a systemic disease requiring medical treatment (Neupane et al. 2021). *Salmonella* in animals affects various species including poultry, cattle, swine, and sheep, often leading to economic losses in livestock industries (García-Díez et al. 2024). Some serotypes, like *S. gallinarum* in poultry, and *S. abortus ovis* in sheep are host-specific, while others such as *S. enteritidis* and *S. typhimurium* are zoonotic and can spread from animals to humans (Haile 2023). Zoonotic transmission of *Salmonella* occurs when bacteria transmit from animals to humans through contaminated food, direct contact, water, or the environment (Adem 2022). Consumption of undercooked meat, poultry, eggs, or contaminated fruits and vegetables is a major source of infection (Cardoso et al. 2021; Srifani et al. 2024). Direct contact with infected animals such as reptiles, birds, and livestock can also transmit the bacteria (Marin et al. 2021). Contaminated water sources, especially those exposed to animal feces, pose a significant risk. Additionally, exposure to contaminated soil farm equipment, and pet food can facilitate bacterial spread. Some animals including cats and dogs carry *Salmonella* asymptomatically, making their detection difficult (Pilau 2022).

Various chemical drugs including antibiotics have played a significant role in controlling *Salmonella* bacteria and its associated infections (Lamichhame et al. 2024). Different antibiotics including fluoroquinolones, third-generation cephalosporin, and macrolides have been used to control *Salmonella* bacteria (Galán-Relaño et al. 2023). However, the irrationality and misuse of antibiotics have led to the emergence of multi-drug-resistant *Salmonella* strains (Alenazy 2022; Bessembayeva et al. 2024). The emergence of multidrug-resistant (MDR) *Salmonella* strains, makes treatment more challenging. Furthermore, these antibiotics may accumulate and produce drug residues in the meat and milk of the animals (Ghimpețeanu et al. 2022). They may disturb the ecological cycle because after excretion they are released into water and soil and contaminate them, hence they are eco-toxic (Adil et al. 2023). To overcome antibiotic resistance, various other alternatives including plant extracts, nanoparticles, essential oils, bacteriophages, and probiotics have been used (Munir et al. 2023; Ahmed and Nawaz 2024; Asghar et al. 2024; Rashid et al. 2024; Raza et al. 2024). Among all alternatives, probiotics have gained significant importance in controlling *Salmonella* infections because they are generally safe and help maintain a healthy gut balance without harming beneficial bacteria (Karabekir et al. 2024). Additionally, they are natural and non-toxic and do not produce drug residues like other antibiotics.

Probiotics are live, non-pathogenic bacteria and yeast that when consumed in appropriate quantities should improve the microbial balance in the host's gut and benefit the host. Additionally, it is involved in the process of metabolism (Sionek et al. 2023). Furthermore, it is well known that probiotics possess certain qualities as they can bind and invade intestinal epithelial cells, resilience to acid pH, bile tolerance, tolerance to pancreatic fluid, and more. These qualities enable them to survive in the digestive system and the gastrointestinal balance is improved (Castro-López et al. 2023). Probiotic microbes can be found in a variety of ecological settings in addition to being a component of intestinal flora. They are not only beneficial for humans and animals but are also used to enhance the growth of aqua creatures including fish (Oleinikova et al. 2024). Probiotic qualities must, however, be understood to be strain- and even tissue-specific. Consequently, neither all bacterial species exert probiotic effect nor all human tissues experience it (Rashid et al. 2024). The immune system is strengthened by early gut colonization, which may offer protection against specific diseases (Wiertsema et al. 2021). Probiotics, whether present in food items or supplements, have become a particularly popular additive in fortified food (Glago et al. 2024). Due to their possible health advantages, they are considered essential ingredients and business goals (Hamad et al. 2022). Probiotics can be consumed in the form of dietary supplements or by incorporating them into various foods and beverages. They are available in both dairy based products, soy products, and some probiotic enriched drinks (Fenster et al. 2019). Scientists have now created novel and cutting-edge techniques including genetic modification and nano-encapsulation that allow probiotics to survive the body's severe GI stressors and processing environments (Putta et al. 2018). Early studies on gut microbiota established the significance of commensal microbes in preserving host health (Anuoluwa et al. 2024). Animals devoid of germs are more vulnerable to pathogen colonization (Litvak and Bäumler 2019), mucosal wounds and chemical intoxication (Salokhiddinovna 2023). The manipulation of the gut microbiota ecosystem to improve the biological, immune-responsive, and cellular metabolism pathways of the host has gained increasing importance due to the significant effects of this microbiome at both the local and systemic levels. As a result, beneficial bacterial species that are part of the mutualistic microbiota and enhance host resilience were identified. *Bifidobacterium* and Lactic acid bacteria (LAB) are among the well-known probiotics; they are among the most researched species with potential health advantages. Because of their obligatory anaerobic characteristics, *Bifidobacterium* cultivation is extremely complex and frequently needs additional attention when it is cultivated in dairy products (Abou-Kassem et al. 2021), like yogurt, and it is also utilized to make probiotic goods. Research studies have demonstrated that probiotics are used as antioxidant, anti-cancerous, anti-allergic, and anti-diabetic agents (Al-Smadi et al. 2023; Kanwal et al. 2024). They are also used to treat respiratory infections (Batista et al. 2023), gastrointestinal disorders (Khoruts et al. 2020), urinary tract infections (Pessoa et al. 2022), and ulcerative colitis (Jadhav et al. 2023). So this review article explores the beneficial effects of probiotics against *Salmonella* infections. It also highlights the mechanism of action of probiotics and their beneficial effects on human and animal health.

2. Sources of probiotics

Probiotics are live microorganisms like bacteria and yeast that may hold health benefits (Noman et al. 2024). Together with the human digestive system, they are present in a variety of foods and supplements (Youssef et al. 2021). Probiotic bacteria that comprise the natural flora of GIT include *Leuconostoc* species, *E. coli*, *Streptococcus*, *Pediococcus*, *Bifidobacterium*, *Lactobacilli*, and *Enterococci* and they are frequently added to well-known fermented functional foods to facilitate their simple administration (Maftei et al. 2024; Kalita et al. 2023). Probiotics-containing foods include fermented foods like kimchi and yogurt (Jang et al. 2024). Additionally, probiotic products can be found as lyophilized powders, capsules, or aqueous solutions. Some of the important sources of probiotics are shown in Fig. 1.

3. Mechanism of action of probiotics

The exact mechanism of action of probiotics against *Salmonella* is not very clear but the human and animal body may benefit from probiotics through four primary mechanisms including enhanced intestinal barrier functioning, immune system modulation, neurotransmitter synthesis, and competitive exclusion of pathogens (Plaza-Diaz et al. 2019). The gastrointestinal tract is noteworthy for having an abundance of nutrients which establishes a suitable environment for the formation of bacterial colonization. Probiotics create a favourable environment that supports the growth of beneficial bacteria and help them thrive while inhibiting the proliferation of harmful pathogens (Khaneghah et al. 2020). When probiotics are taken as supplements, they produce certain substances, like volatile unsaturated lipids, which can lower the pH in the gastrointestinal tract (Sadeghi et al. 2022). Since many harmful bacteria cannot survive in an acidic environment, the decrease in pH created by probiotics makes the gut less hospitable to these

***Fig. 1**: Different sources of probiotics (www.canva.com)*

pathogens. As a result, the growth of harmful bacteria is inhibited, helping to protect the body from infections (Biswasroy et al. 2021). Probiotics prevent infections from flourishing in the gastrointestinal tract by fighting with them for vitality and active sites. Moreover, probiotics are responsible for the production of chemicals like hydrogen peroxide, metabolic acids, and bacteriocins hence reducing the number of harmful bacteria in the stomach (Fantinato et al. 2019; Ahire et al. 2021; Chuong and Tri 2024). Probiotics have been shown to increase mucin protein expression (Chang et al. 2021), regulate tight junction proteins synthesis such as occludin and claudin 1, and ultimately improve gut defense responses (Bu et al. 2022). All these mechanisms including production of antimicrobial substances, immunomodulation, and enhanced mucus production finally contribute to the improvement of intestinal barrier function. Some of the beneficial effects of probiotics are given below.

4. Probiotics directly prevent pathogen development

There are numerous ways that probiotics directly combat pathogens: they can produce antimicrobials, remove pathogens from mucus, or eliminate infectious agents by quorum quenching and co-adhesion (Panwar et al. 2021). Bacteriocins, euterins, organic acids, and hydrogen peroxides are the antimicrobials that are developed by probiotic strains (Chen and Zhang 2023). The main source of antibacterial activity is the synthesis of metabolic acid through several probiotic strains including *Bifidobacterium* and LAB (Ahansaz et al. 2023). Similarly, hydrogen peroxide producing *Lactobacillus* species, including *L. fermentum, L. jensenii*, and *L. acidophilus* are associated with a reduced population of anaerobic bacteria, such as *Salmonella*, *Gardnerella*, *Bacteriodes*, *Prevotella*, and *Mycoplasma* spp. (McLaughlin et al. 2024). One famous antibacterial compound generated by *L. reuteri* is reuterin (3-hydroxy propionaldehyde), which is believed to work by thiol oxidation in the target infectious agent (Duda-Chodak et al. 2023). Reuterin is significant because it may be able to selectively stop harmful gut bacteria from growing without eliminating beneficial species. This property enables *L. reuteri* to eliminate intestinal intruders while maintaining the integrity of the normal gut microbiota. Reuterin exhibits antibacterial action against *Staphylococcus*, a frequent chronic wound infection (Ma et al. 2023). Another metabolic byproduct of *Lactobacilli* is diacetyl (2, 3-butanedione), which has a broad range of antibacterial activity against infections of both the gram-negative and gram-positive varieties (Fidan et al. 2022). Furthermore, Bacteriocins, a unique family of probiotic metabolites, are tiny peptides produced by bacteria that have a broad spectrum of antibacterial action both *in vitro* and *in vivo* environments (Tang et al. 2022). *Staphylococcus pyogenes*, a pathogen that causes pharyngitis and cutaneous infections, is effectively inhibited by the bacteriocins generated by the oral epithelium-associated bacteria *Streptococcus salivarius* (Tagg et al. 2023). Oral prophylactic dosing of *Staphylococcus salivarius* has shown effective results against recurrent *S. pyogenes* infections in children and adults (Kryuchko et al. 2021). Certain probiotic species, including *B. longum, L. rhamnosus,* and *L. delbrueckii* can clump together with other microorganisms such as *Candida albicans* and *S. aureus*. This ability is believed to be linked to their antimicrobial properties which helps inhibit harmful bacteria (Fathima et al. 2022). *In vivo*, research is necessary even though several *in vitro* investigations have demonstrated the ability of probiotic aggregation to drive pathogens out of epithelial cells (Anjum et al. 2022). Apart from generating antimicrobial agents and collaborating, probiotic strains can eliminate intestinal pathogens from the intestinal epithelium. Displacement may be caused by certain surface chemicals produced by *Lactobacilli*, such as extracellular polysaccharides which enable *L. paracasei* to displace pathogenic bacteria by competitively adhering to extracellular cells (de la Rosa et al. 2022). The pathogen's quorum sensing (QS) system is inhibited, which is another newly discovered antibacterial mechanism of LAB (Azimi et al. 2020; Bioff et al. 2024; Dolgun et al. 2024). Most bacteria use QS for pathogenicity, biofilm development, and resistance to host defense, including *Pseudomonas aeruginosa* and *S. aureus*, which are commonly seen in chronic wounds (Qin et al. 2022). Probiotics can, however, disrupt the pathogen's QS. It has been demonstrated that *L. plantarum* specifically inhibits *P. aeruginosa's* synthesis of QS signaling molecules (acyl-homoserine-lactone) and decreases the development of biofilms (Salman et al. 2023; Saleena et al. 2024). Importantly, in burn wounds of mice, *L. plantarum* has also been demonstrated to suppress the growth of *P. aeruginosa* (Dahshan et al. 2023).

5. Impact on intestinal disorders

The gastrointestinal tract of humans and animals hosts a large number of commensal bacteria that form an active community with profound implications for human physiology (Shehata et al. 2022). However, the gut microbiome's metabolic activity has both beneficial and detrimental effects on host health. The intestine is essential for digestion and absorption of nutrients, as well as for maintaining the mucosal barrier. Antibiotics, probiotics, prebiotics, and fecal transplants can be used to modify the intestinal microflora (Shahverdi 2016). One useful strategy for treating intestinal disorders is to replenish a healthy gut flora. An imbalance in gut microflora can cause fibrosis and health issues like ulcers, inflammatory diseases, and antibiotic-associated diarrhea (Saber et al. 2017). Additionally, there are some studies which back the theory that certain human malignancies, particularly those of the gastrointestinal tract, are caused by microbial dysbiosis (Pereira-Marques et al. 2019). According to Jang et al. (2019), probiotics can improve the immunological microenvironment, boost microbial richness and variety, promote the synthesis of the enzyme lactase, and improve intestinal permeability (Sehrawat et al. 2021). Ahmad et al. (2023) confirmed that a fermented diet containing beneficial microorganisms including *Lactobacillus* and LAB helps to boost immunity and plays an important role in controlling Diabetes mellitus type 2. Similarly, in another study conducted by Ansari et al. (2024) confirmed that a fermented diet helps to reduce the burden of heavy metals in the GI tract and reduce oxidative stress and prevent the host from the tumor growth. All these studies confirmed that consumption of fermented food containing probiotics can prevent humans and animals from the different ailments.

6. Probiotics function in intestinal wound healing

Probiotics play an important role in intestinal wound healing by promoting epithelial cell proliferation, strengthening barrier integrity, and stimulating immune responses (Kim et al. 2022; Issa 2024). Beneficial bacteria like *Lactobacillus* and *Bifidobacterium* produce bioactive compounds such as short-chain fatty acids, which serve as an energy source for epithelial cells and stimulate mucus production, aiding tissue repair (Virk et al. 2024). Probiotics regulate inflammatory pathways by producing pro-inflammatory cytokines and enhancing anti-inflammatory responses, generating a balanced environment for healing (Cristofori et al. 2021). By lowering inflammation, probiotics accelerate recovery of intestinal injuries caused by *Salmonella* infections or surgery (Matzaras et al. 2023). They also increase gut barrier function, preventing further damage and reducing permeability. Probiotics also stimulate immune defenses by increasing secretory IgA production and modulating dendritic cells, which increase protection against infections (Raheem et al. 2021). Their role in reducing oxidative stress helps prevent additional tissue damage. In post-surgical recovery, probiotics support faster healing and reduce complications (Shi et al. 2022). They maintain gut microbial balance, preventing dysbiosis that can delay healing. By restoring homeostasis, probiotics create a healthier gut environment. Their immunomodulatory effects contribute to long-term intestinal health (Russo et al. 2019). Probiotic interventions offer an effective natural therapeutic strategy for intestinal wound healing and recovery.

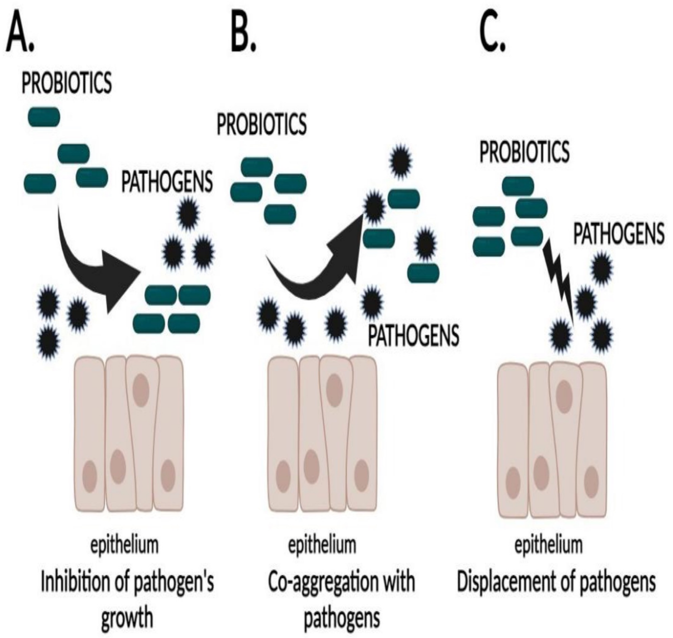

Fig. 2*: Antimicrobial properties of probiotics against harmful microorganisms on the skin and mucosal areas (www.biorender.com)*

7. Immunomodulation by Probiotics

Probiotics are known to improve intestinal and systemic health by modulating the immune system (Imran et al. 2023). The probiotics affect immunity mainly by stimulating innate immunity effector cells such as macrophages, dendritic cells (DC), T lymphocytes, and natural killer (NK) cells (Yousefi et al 2019). These cells play a role in repairing the GI and skin barriers (Alagón Fernández del Campo et al. 2019). However, the immunomodulatory properties of probiotics differ by species and strains. For example, *L. rhamnosus* and *L. sakei* have been shown to enhance macrophage activity (Mazziotta et al. 2023), while *L. plantarum* enhanced peritoneal macrophage phagocytic activity *in vivo* (Wang et al. 2020). These activities are mostly associated with the activation of IL-22, tumor necrosis factor alpha (TNF-α), IL-6, IL-8, and IL-12 production (Valeri and Raffatellu 2016). Additionally, *L. reuteri* and *L. jensenii* strains can produce cytokine IL-22, which is mostly secreted by intraepithelial immune cells (Wu et al. 2024). The metabolites of probiotic strains can attach to and activate aryl hydrocarbon receptors (AhR) of DC and macrophages, which then activates epithelial cells (Pinto et al. 2023). TNF-α is another cytokine that is generated by systemic probiotic delivery. Mostly generated by macrophages, it is the most important cytokine in the innate immune response (Cristofori et al. 2021). Raheem et al. (2021) showed that *L. casei* stimulated the production of TNF-α in addition to IFNγ and IL-10 in healthy mice. Additionally, *L. fermentum* therapy led to higher TNF-α expression, which is linked to higher neutrophil infiltration (Mazziotta et al. 2023), which may aid in the resolution of infection. Treatment with *Lactobacilli* was also associated with the release of IL-8, which is essential for the proper activity of neutrophils (Škrlec et al. 2017). Kaur and Ali (2022) demonstrated that *Lactobacilli* influence the cytokines of innate immune cells and the release of IL-10 and IL-12, which mediate the innate and adaptive immune responses. Additionally, *Lactobacilli* activate macrophages, intraepithelial T lymphocytes, and NK cells (Rizzello et al. 2011). However, they have very strain-specific effects on the induction of regulatory T cells and Th1 cells. Accordingly, certain *Lactobacilli* isolates have immunosuppressive and anti-inflammatory properties, while other isolates have pro-inflammatory properties and can stimulate the immune system, which helps eliminate pathogens.

8. Anti-allergic properties of probiotics

Allergies have become increasingly common, with nearly half of people in Europe and North America affected. These allergic reactions, as described by Shahali and Dadar (2018), are often triggered by antigens or common environmental chemicals. In addition to hay fever, other common allergic reactions include food allergies, drug hypersensitivity, insect stings, asthma, atopic eczema, dermatitis, rhinitis, urticarial, and angioedema (Lopez-Samntmarina et al. 2021). Harata et al. (2016) suggest that the gut microbiota can be targeted therapeutically to manage allergic diseases, as it has a significant impact on the immune system and inflammation. Allergic inflammation is driven by interleukins (ILs) released by allergen-sensitized Th2 cells, such as IL-4, IL-5, and IL-1, as well as basophils, mast cells, and eosinophils (Di Costanzo et al. 2016). These ILs influence B lymphocytes, causing them to produce increased levels of allergen-specific and total immunoglobulins E (IgE) in circulation (Galli et al. 2020). Probiotics might also produce immunosuppressive cytokines like IL-10 (Liang et al. 2022). Di Costanzo et al. (2016) also confirmed that probiotics may exert anti-allergic effects by enhancing the level of helper T cells, particularly Th1 and Th2 cells. Probiotics are thought to suppress the Th2-dominated immune response while promoting the Th1 response. Additionally, according to Ma et al. (2019), probiotics can alter dendritic cell activity, which facilitates the production of regulatory T cells. These cells help balance the Th1 and Th2 ratio and regulate excessive immune responses. *Lactobacillus* in particular, plays a role in activating regulatory T cells which are essential for maintaining immune balance by producing immunosuppressive cytokines and regulating the production of IgA, IgG, and IgE (Latif et al. 2023). In another study, when *Lactobacillus reuteri* was orally administered, it alleviated allergic diarrhea and improved the composition of gut microbiota. This led to an increase in transforming growth factor beta (TGF-β), transforming factor (FoxP3), and IL-10, while also down-regulating the production of Th1 and Th2 cytokines (Peng et al. 2023). Furthermore, it reduced serum IgE levels and mast cell activation. These findings support the idea that probiotics obtained from bacteria can help alleviate allergic reactions by modulating the gut microbiota and enhancing immunological tolerance (Huang et al. 2017).

9. Anti-hypocholesterolemic effect of probiotics

Lowering of blood cholesterol levels can be achieved with the use of probiotics. They can lower the body's cholesterol levels either directly or indirectly and have better effects on blood parameters (Hambakodu et al. 2024). According to Thakkar et al. (2016), direct mechanisms include the suppression of the production of new cholesterol by hypocholesterolemia-causing agents such as whey protein, lactose, uric acid, and orotic acid. Furthermore, it reduces cholesterol absorption by the stomach by binding, breaking down, and absorption. Probiotics reduce cholesterol indirectly through the deconjugation of bile salts such as taurodeoxycholic acid and conjugated glycodeoxycholic acid by synthesizing bile salt hydrolase (Liu et al. 2024). According to Rezaei et al. (2017), deconjugated bile salts are less likely to be absorbed through the colon, which prevents the bile from being circulated enterohepatically and increases excretion in the stools. Research on both humans and animals has demonstrated that probiotics have a hypocholesterolemic effect. *L. brevis* MW365351 and *Levilactobacillus brevis* MT950194 have exhibited hypocholesterolemic characteristics (Munir et al. 2022). They are said to lower cholesterol, increase cholesterol excretion in the stool, and convert bile into free cholic acid. A probiotic complex of *Bifidobacterium*, *Lactobacillus*, and *Pediococcus* improves lipid metabolism (Chen et al. 2022). The cholesterol levels of medium and high-dose probiotic groups were significantly lower after 10 weeks of the investigation (Galli et al. 2020). Triglycerides, hepatic cholesterol, and serum cholesterol decreased when the investigated probiotic strain was consumed, whereas bile acid excretion in the feces increased. Total cholesterol (23.03%), low-density lipoprotein (28.00%), and the atherosclerosis index significantly declined by 34.03% after receiving *L. plantarum* DMDL 9010 at a rate of 10^9 cells per day (Liu et al. 2017). In another study, scientists have undertaken research on the expression of genes in hypercholesterolemia with the use of probiotics (Liang et al. 2021). This study assessed how *Lacticaseibacillus paracasei* regulates two key genes: cytochrome P450 7A1 linked to cholesterol metabolism and 3-hydroxy-3-methyl glutaryl coenzyme reductase. The dosage given to male Wistar rats was 10^{10} CFU for 21 days. Aspartate aminotransferase (AST) and alanine aminotransferase (ALT) decreased in tandem with a considerable drop in cholesterol levels. Real-time polymerase chain reaction was also used to detect the sharp decrease in the adipose tissues' HMGCR and CYP7A1 gene expression (Dehkohneh et al. 2019).

10. Future Prospects

The potential of probiotics in the control of *Salmonella* infections in both animals and humans opens new avenues for research and application. Future studies should focus on identifying specific probiotic strains with superior antimicrobial properties to increase their efficacy against *Salmonella*. Advanced biotechnological approaches, such as genetic engineering and nanotechnology, could be explored to develop next-generation probiotic formulations with enhanced stability and targeted delivery. Additionally, more *in vivo* studies and clinical trials are needed to validate the effectiveness of probiotics in real-world conditions. Investigating the synergistic effects of probiotics with natural antimicrobials such as plant-derived compounds or probiotics may further enhance their protective role. The development of probiotic-based feed additives and functional foods could serve as sustainable

Table 1 Beneficial effects of probiotics against various disorders

Disease	Strain	Results	Efficacy	Reference
Allergic reactions	*Lactobacillus* multiple strains	↑ IFN-γ, ↓ IL-2	Low	(Yang et al. 2021a)
Allergic reactions	*Lactobacillus plantarum*	↓ IL-10 ↑ IFN-γ	Low	(Yang et al. 2021b)
Antibiotic-associated diarrhea	*Lactobacillus* and *Bifidobacterium* strains	Delayed onset of diarrhea	Moderate	(Trallero et al. 2019)
Chronic diarrhea	*Lactobacillus plantarum* CCFM1143	Altered gut microbiota, Improved immunity	Low	(Yang et al. 2021b)
Hypercholesterolemia	*Lactobacillus casei* (pWQH0I), *Lactobacillus plantarum* (AR113)	↓ TC in the liver by bile salt hydrolase and ↑ CYP7A1 gene expression by LDL-C	Low	(Wang et al. 2019)
Hypercholesterolemia	*Lactobacillus fermentum* MGM60397	↓ Cholesterol ↑ LDLR gene expression	Low	(Palaniyandi et al. 2020)
Radiation-induced diarrhea	*Lactobacillus acidophilus* and *Bifidobacterium animalis*	↓ severe diarrhea ↓ abdominal pain	Moderate	(Linn et al. 2019)
Ulcerative colitis	*Lactobacillus lactis*	↓ colitis	Low	(Alves et al. 2023)

alternatives to antibiotics in both veterinary and human medicine. Also, extended research is needed for the assessment of lasting consequences of probiotic pharmaceuticals on the well-being and fertility of animals and food safety, making them promising substitutes to antibiotics. The regulatory framework should also be refined to ensure the safety and efficacy of probiotic interventions.

13. Conclusion

Probiotics serve as promising antioxidant agents in the control of *Salmonella* infections in animals and humans. Their ability to enhance gut microbiota, boost immune responses, and counteract oxidative stress contributes to their protective role against *Salmonella* colonization and infection. Unlike antibiotics, probiotics offer a natural and sustainable solution with fewer side effects and reduced risks of antimicrobial resistance. However, challenges such as strain specificity, optimal dosages, and host-dependent effects must be addressed through rigorous scientific research. Future advancements in probiotic formulations and their integration into animal feed and human diets could revolutionize disease-preventive strategies. Overall, harnessing the antimicrobial potential of probiotics represents a promising strategy for mitigating *Salmonella*-related health risks while promoting gut health and overall well-being.

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