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A Comprehensive Review of Probiotic Mechanisms and Their Implementation in Gastrointestinal Health Management

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ABSTRACT

Probiotics, which are live microorganisms that benefit the host, have been shown to be effective in preventing and treating antibiotic-associated diarrhea (AAD). However, the specific molecular mechanisms of individual probiotic strains remain poorly understood. This study aims to explore strain-specific approaches for managing gastrointestinal disorders and to provide a scientific overview of the benefits and mechanisms of probiotics in maintaining and improving gut health through complex and interconnected pathways. A systematic literature search was conducted using keywords such as "probiotics," "gut microbiota," "strain-specific mechanisms," "gastrointestinal health," "host-microbe interaction," and "synbiotics," across reputable databases including PubMed, Scopus, ScienceDirect, and Google Scholar. The methodological quality and strength of evidence for each study were assessed using the GRADE (Grading of Recommendations, Assessment, Development and Evaluation) framework. Numerous studies have confirmed that probiotics help prevent and treat AAD and may also reduce the risk of irritable bowel syndrome (IBS) and inflammatory bowel diseases. Clinical trials have also shown promising results regarding the ability of various probiotic strains to balance the mucosal immune system and gut microbiota. However, comprehensive research on the synergistic interactions between probiotic and prebiotic strains remains limited. Therefore, future studies should focus on cross-omic approaches, exploration of local strains from traditional diets, and personalized strategies to optimize the efficacy of probiotics in supporting gastrointestinal health.

Keywords: *Probiotics, Gut Microbiota, Digestive Health*

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INTRODUCTION

The gastrointestinal tract plays an important role as a major component of the immune system and has a significant impact on overall health. The balance of the gut microbiota is key in maintaining gastrointestinal function, as imbalances can lead to various disorders such as diarrhoea, irritable bowel syndrome, constipation, and metabolic diseases. Diarrhoea itself remains a serious global health problem, with millions of cases and high mortality rates each year, including in Indonesia where diarrhoea is the leading cause of death for infants and toddlers. Generally treated with antibiotics, the treatment of diarrhoea is now facing challenges in the form of increasing antimicrobial resistance (Tari et al., 2020).

As an alternative, the use of probiotics is gaining ground due to their ability to maintain microbiota balance, boost the immune system, and inhibit the growth of pathogenic bacteria in the gut. Probiotics, which are live microorganisms, provide health benefits when consumed in sufficient amounts. To support the effectiveness of probiotics and maintain a healthy digestive tract, it is important to adopt a healthy diet high in fibre, limit unnecessary antibiotic use, and manage stress effectively (Komalasari & Wahyu Krisna Yoga, 2022).

Most probiotic microorganisms are derived from bacteria, particularly lactic acid bacteria (LAB) and Bifidobacterium, which have been widely used commercially and are considered safe for long-term consumption. The effectiveness of probiotics largely depends on their ability to survive the journey through the digestive tract until they reach the gut, where they provide optimal functional benefits. Probiotics must be resistant to stomach acid, bile salts, and digestive processes in order to live and colonise in the gut, thus balancing the gut microflora, inhibiting the growth of pathogenic bacteria, and boosting the immune system (Junita & Mustakim, 2024; Komalasari & Yoga, 2022).

To provide optimal health benefits, probiotics must be present in sufficient amounts in the gut. The stability of the probiotic amount must also be maintained during storage and processing of the product so that it remains effective when consumed. The minimum concentration of probiotic cells in food products at the time of consumption is an important factor to ensure the expected health effects. Therefore, probiotics are recommended to meet the minimum bio-value (MBV), which is the minimum number of probiotic cells required to provide health benefits. According to the International Dairy Federation (IDF) recommendation, this MBV index should reach more than 10^7 CFU/g. In addition, the effectiveness of probiotics also depends on the daily intake consumed, with a minimum recommendation of about 10^9 cells per day. Meanwhile, the United States Food and Drug Administration (FDA) sets the standard for the minimum amount of safe and beneficial probiotics in a product at 10^6 CFU/mL (Setiarto, 2016).

Probiotics, which are live microorganisms that provide health benefits to the host, have been shown to be effective in preventing and treating antibiotic-associated diarrhoea (AAD). Antibiotic use often disrupts the balance of the gut microbiota, which can lead to AAD with prevalence varying from 5% to 35% in patients receiving antibiotic therapy (Goodman et al., 2021). A meta-analysis involving 42 studies with a total of 11,305 participants showed that co-administration of probiotics with antibiotics can reduce the risk of AAD by 37% (risk ratio [RR] = 0.63; 95% CI 0.54 to 0.73, $p < 0.00001$) (Goodman et al., 2021). In addition, research by McFarland and Li (2024) also found that the probiotic strain Saccharomyces boulardii CNCM I-745 significantly reduced the incidence of AAD and Clostridioides difficile infection (CDI) in China, with RRs of 0.43 and 0.30, respectively (McFarland & Li, 2024). Probiotics not only reduce the frequency of diarrhoea, but also the duration and severity of symptoms, making them a valuable option in the management of patients receiving antibiotic therapy (Muliana et al., 2024). Thus, the use of probiotics as preventive and therapeutic interventions in the context of AAD shows significant potential to improve gastrointestinal health, especially in vulnerable populations such as the elderly and hospitalised patients.

One aspect that has been under-researched in previous studies is how combinations of different probiotic strains can interact synergistically in improving digestive health. Several studies have shown that the effectiveness of probiotics can be enhanced by the presence of prebiotics in synbiotic formulations, which serve as a source of nutrients for probiotics and help colonise beneficial bacteria in the gut. However, in-depth research on the mechanism of action and specific effectiveness of combining various probiotic strains with prebiotics is still limited, so further research is needed to understand the role of synbiotics more comprehensively in maintaining the balance of gut microbiota and supporting digestive system health (Ramadhani et al., 2024).

One important aspect that has received little attention in probiotic studies is the strain-specific mechanism of action, especially in the context of molecular interactions between probiotic microbes and their hosts. Although a number of clinical trials have shown promising results on the effectiveness of probiotics in preventing and treating gastrointestinal disorders such as antibiotic-associated diarrhoea, scientific understanding of the specific mode of action of each probiotic strain at the molecular level is still limited. The complex interactions between probiotics and intestinal epithelial cells, the mucosal immune system, and the metabolites they produce have not been fully characterised. This knowledge gap hinders the development of more precise and evidence-based probiotic formulations that target specific gastrointestinal disorders more effectively. Therefore, this study specifically aims to identify and summarise the key molecular mechanisms underlying the probiotic activity of various strains, as well as examine the potential of strain-based approaches in the therapy of gastrointestinal disorders.

In addition, although the concept of synbiotic combinations of probiotics and prebiotics has been widely introduced as a promising strategy to improve the colonisation effectiveness and functionality of probiotics, in-depth studies on the synergistic interactions between probiotic strains and their collaborative mechanisms with prebiotics in supporting gut microbiota health are still limited. This study also highlighted limited data on the effectiveness of combinations of probiotic strains and prebiotics under different physiological conditions. On the other hand, the results of the preliminary survey showed a low understanding of the importance of probiotic consumption to maintain a healthy digestive system. Thus, this study aims not only to compile a scientific review of the mechanisms and benefits of probiotics, but also to provide a scientific basis for public education efforts and the development of more appropriate probiotic and synbiotic-based health products.

METHODS

This study used a systematic review approach to identify, evaluate, and summarise the current scientific evidence on the mechanism of action of probiotics, particularly strain-specific ones, in supporting human gastrointestinal health. The literature search process was conducted systematically through several leading scientific databases such as PubMed, Scopus, ScienceDirect, and Google Scholar using keywords such as 'probiotics', 'gut microbiota', 'strain-specific mechanisms', 'gastrointestinal health', 'host-microbe interaction', and 'synbiotics'. Articles searched were limited to publications in English and Indonesian published between 2021 and 2024.

The inclusion criteria used in this study included clinical trial studies and systematic reviews or meta-analyses that evaluated the effect of probiotics on human gastrointestinal health. These studies should highlight the biological or molecular mechanisms of specific probiotic strains, and may include synergistic interactions between probiotics and prebiotics (synbiotics) that impact the gut microbiota. Only articles that include information on strain type, dose, and clinical or physiological parameters relevant to gastrointestinal function will be included. In contrast, animal studies without clinical relevance, case reports, editorials, opinion pieces, or articles that did not clearly present empirical data or the mechanism of action of probiotics were excluded from the analysis (exclusion criteria).

Data extraction was performed by two independent researchers using a standardised form that recorded core information from each study, such as study design, population, type of probiotic used, dose, reported mechanism of action (e.g. immune modulation, pathogen inhibition, or metabolite production), and clinical outcomes related to gastrointestinal health. Any discrepancies in the data extraction process were resolved through discussion with a third researcher to reach consensus. To assess the methodological quality and strength of evidence of each included study, the GRADE (Grading of Recommendations, Assessment, Development and Evaluations) instrument was used. This instrument assesses the risk of bias, consistency of results, accuracy of effect estimates, relevance to the target population, as well as potential publication bias, thus enabling a transparent and systematic assessment of the strength of the available scientific evidence.

The results of this study are expected to provide an understanding of the urgency of probiotic consumption in maintaining a healthy digestive tract (Creswell, 2018).

RESULTS

1. Physiological Mechanisms of Probiotics in the Digestive System

Based on a survey of several studies that have been conducted, it was found that there are various types of probiotics that are beneficial in supporting the health of the human digestive tract and the species used in probiotic products. These probiotics can be found in various fermented food and beverage sources. The species and various types of probiotic products can be seen in Table 1 and Table 2 below.

Probiotics support gastrointestinal health through a variety of key physiological mechanisms. One of these is nutrient competition, where probiotics compete with pathogenic bacteria for resources such as carbohydrates and amino acids, thereby limiting the growth of harmful microbes. In addition, probiotics such as Lactobacillus spp. and Bifidobacterium spp. produce organic acids (e.g. lactic and acetic) that lower gut pH, creating an inhospitable environment for pathogens.

Some strains also produce bacteriocins, which are antimicrobial compounds that directly inhibit pathogenic bacteria. Another important mechanism is the strengthening of tight junctions between intestinal epithelial cells, which plays a role in maintaining mucosal integrity and preventing bacterial translocation. The combination of these mechanisms contributes to the reduction of diarrhoea, improved nutrient absorption and resistance to gastrointestinal infections.

Table 1. Types of Species in Probiotic Products

Bifidobacterium	*Lactobacillus*	Others
B.longum	*L.casei*	*Saccharomyces cerevisiae*
(*B.longum* subsp.		
longum)	*L.acidophilus*	*Enterococcus faecium*
B.infantis	*L.rhamnosus*	*Enterococcus faecalis*
(*B.longum* subsp.		
infantis)	*L.paracasei*	
B.breve	*L.johnsonii*	
B.animatis subsp. *Lactis*	*L.plantarum*	

B.bifidium	*L. reuteri*
B.adolescentis	*L.salivarius*
	L.fermentum
	L.bulgaricus

2. Efek Strain-Spesifik pada Mikrobiota Usus

Various probiotic strains have significant differences in their effectiveness against certain clinical conditions. For example, Lactobacillus rhamnosus GG is effective in preventing antibiotic-associated diarrhoea, while Saccharomyces boulardii shows good results in the treatment of Clostridioides difficile infection. These differences are due to metabolic properties, colonisation ability and host cell receptor affinity that vary between species.

Table 2. Specific Characteristics and Mechanism of Action of Probiotic Strains

Species	Main Characteristics	Working Mechanism
L. acidophilus	Acid & bile resistant, strong colonization	Lactate production, nutrient competition, pH modulation
L. rhamnosus GG	Adhesion to mucosa is high	Inhibits pathogens, strengthens tight junctions
L. plantarum	High protein fermentation	Anti-inflammatory, mucosal protection
B. bifidum	Complex fiber fermentation	SCFA production, immune stimulation
S. boulardii	Antibiotic resistant yeast	Toxin neutralization, immunomodulation
E. faecium	Active proteolysis	Inhibition of pathogens, balance of microflora

Table 3. Some Probiotic Products to Support Digestive Health

No	Types of Probiotics	Food/Beverage Source	Key Digestive Benefits
1	*Lactobacillus acidophilus*	Yogurt, kefir, tempeh	Aids lactose digestion, inhibits pathogenic bacteria
2	*Lactobacillus rhamnosus*	Yogurt, fermented milk	Prevents diarrhea, boosts immune system
3	*Lactobacillus casei*	Yogurt, keju, kefir	Supports balance of gut microflora, aids metabolism
4	*Lactobacillus plantarum*	Kimchi, sauerkraut, tempeh	Reduces intestinal inflammation, improves protein digestion
5	*Lactobacillus reuteri*	Yogurt, fermented milk	Reduces symptoms of irritable bowel syndrome (IBS), boosts immunity
6	*Bifidobacterium bifidum*	Fermented milk, yogurt	Aids fiber digestion, increases short-chain fatty acid production
7	*Bifidobacterium lactis*	Cheese, yogurt, fermented milk	Reduces constipation, improves colon health

No	Types of Probiotics	Food/Beverage Source	Key Digestive Benefits
8	*Streptococcus thermophilus*	Yogurt, kefir	Helps digest lactose, reducing symptoms of lactose intolerance
9	*Saccharomyces boulardii*	Probiotic supplements, water kefir	Prevents antibiotic-induced diarrhea, fights intestinal infections
10	*Enterococcus faecium*	Fermented milk, cheese	Balances gut microbiota, aiding protein digestion

Table 4. Comparison of Strain-Specific Probiotic Clinical Outcomes

Author (Year)	Strains	Dose	Duration	Clinical Results	Effect Size
Goodman et al. (2021)	*L. rhamnosus GG*	10^9 CFU/day	10 days	AAD Decrease	RR = 0.63
McFarland & Li (2024)	*S. boulardii CNCM I-745*	5×10^9 CFU/day	14 days	AAD & CDI Decrease	RR = 0.43 (AAD), 0.30 (CDI)
Muliana et al. (2024)	*L. reuteri*	10^8 CFU/day	7 days	IBS symptoms reduced	↑Quality of life
The Last Supper (2024)	*B. lactis*	10^9 CFU/day	4 weeks	Constipation reduction	↑Frequency of bowel movements

The interaction between probiotics and the host takes place in a complex manner through molecular signalling pathways, including the activation of NF-κB and MAPKs, which influence mucosal immune responses. Some strains such as L. rhamnosus are able to stimulate Toll-like receptors (TLR2 and TLR9) in intestinal epithelial cells, resulting in modulation of anti-inflammatory cytokines such as IL-10 and a decrease in pro-inflammatory cytokines such as TNF-α. In addition, certain strains can increase the production of secretory IgA, which strengthens the gastrointestinal mucosal defence against pathogens.

The combination of probiotics and prebiotics known as synbiotics provides a greater synergistic effect than single use. Prebiotics such as inulin and FOS become the main substrates for fermentation by probiotics, increasing short-chain fatty acid (SCFA) production and aiding colonisation of beneficial bacteria. Studies show that the combination of B. lactis and inulin significantly increases SCFA concentrations and reduces constipation symptoms. The combination of L. acidophilus with galactooligosaccharides (GOS) also improves mucosal immune efficiency and microflora balance.

DISCUSSION

Probiotics are live microorganisms, mainly from the genus Lactobacillus, Bifidobacterium, and Saccharomyces, which, when consumed in sufficient quantities, provide health benefits to their hosts by balancing the gut microbiota (Gao et al., 2022). They are able to colonise the mucosal surfaces of the gastrointestinal tract, modulate immune responses, strengthen the intestinal epithelial barrier, and suppress pathogen growth. Probiotics play a role in the fermentation of non-digestive substrates through their interaction with prebiotic-fibre foods such as inulin, fructooligosaccharides (FOS), and galactooligosaccharides (GOS) that selectively favour the growth of commensal bacteria. This fermentation produces short-chain fatty acids (SCFA) such as acetate, propionate and butyrate (Wang et al., 2021).

SCFAs serve as the main energy source of colonocytes, strengthen the intestinal barrier, and have anti-inflammatory effects by modulating the production of proinflammatory cytokines (Kumari et al., 2024). Furthermore, probiotics and prebiotics can form synbiotics-a synergistic relationship that strengthens the colonisation and metabolic activity of beneficial microbes in the gastrointestinal tract (Marnpae et al., 2024). Synbiotics increase SCFA production and reduce the Firmicutes/Bacteroidetes ratio, which is important for maintaining microbiota balance and metabolic health.

Probiotics play an important role in maintaining the health of the gastrointestinal tract through various mechanisms of mucosal defence, protective functions, and modulation of the immune system. Their presence supports the integrity of the epithelial layer, strengthens the mucosal layer, and contributes to the processes of peristalsis and epithelial desquamation, which collectively play a role in preventing pathogen colonisation. In addition, probiotics stimulate the secretion of immunoglobulin A (IgA), which serves as a mucosal immune defence to inhibit adhesion of pathogenic microorganisms. Thus, probiotics not only play a role in maintaining a balanced gut microbiota, but also in modulating local and systemic immune responses.

The human gastrointestinal tract is an ecosystem inhabited by various types of microorganisms (microflora) that play an important role in maintaining the physiological balance of the body. Under conditions of eubiosis, which is when there is a balance between the populations of commensal bacteria in the gastrointestinal tract, these microflora contribute to a variety of biological functions, including digestion, nutrient synthesis and modulation of the immune system. When microflora dysbiosis occurs, which can be caused by an unhealthy diet, stress, or antibiotic use, the normal functions of the microflora are disrupted, increasing the risk of various health disorders. Therefore, maintaining a balanced gastrointestinal microflora is an important factor in maintaining overall health (Hasibuan & Kolondam, 2017).

Numerous studies have shown that consumption of probiotic-containing foods contributes significantly to the health of the gastrointestinal tract and plays a role in the prevention of various gastrointestinal disorders. Ardilla et al. (2022) reported that typical Indonesian fermented foods such as tempeh, tapai, green tea, sayur asem, and bekasam-contain probiotic microorganisms such as Lactobacillus plantarum, Lactobacillus curvatus, Lactobacillus GG, as well as local yeasts such as Saccharomyces cerevisiae and Candida tropicalis. These microbes play a role in improving the composition of the gut microflora, inhibiting the growth of pathogenic microorganisms, and producing bioactive compounds such as organic acids, antimicrobial peptides, and digestive enzymes that play a role in improving the physiological function of the gastrointestinal tract and the body's immunity (Ardilla et al., 2022).

One important aspect in the context of gut health is dysbiosis, a condition of gut microbiota imbalance characterised by a decrease in the number of beneficial microorganisms and an increase in pathogenic microbes. Dysbiosis can be caused by a variety of factors, including consumption of low-fibre processed foods, overuse of antibiotics, chronic stress and sedentary lifestyle. It contributes to disorders such as chronic diarrhoea, irritable bowel syndrome (IBS), mucosal inflammation, and metabolic disorders. Dysbiosis leads to disrupted production of important metabolite compounds such as short-chain fatty acids (SCFAs), decreased production of endogenous vitamins such as vitamin K and B12, and weakened gut mucosal defences, which can increase gut permeability (leaky gut) and the risk of systemic inflammation. Under these conditions, probiotic administration is a promising physiological solution due to its ability to rebalance microbiota composition, strengthen local immune responses, and improve intestinal epithelial barrier integrity (Dewi et al., 2021).

Although the benefits of probiotics have been scientifically proven, public understanding of the importance of consuming probiotic-rich foods is still relatively low. Lack of education leads to low consumption of fermented foods such as kombucha, which actually has great potential in supporting digestive health (Miladiarsi et al., 2022).

Therefore, wider socialisation efforts are needed to increase public awareness of the importance of probiotics in daily life. In addition to education, the development of probiotic products based on local food ingredients is also an important aspect in the utilisation of Indonesia's food resources. Various traditional fermented foods such as tempeh, tape, and bekasam are known to contain natural probiotics, but further research is needed to optimise the fermentation process to increase the probiotic content (Ramadhani et al., 2024). In addition, the combination of probiotics with prebiotics in a synbiotic product may increase its effectiveness in maintaining the balance of gut microbiota. Therefore, further exploration of the synergy of probiotics in local fermented products is needed so that their health benefits can be optimised for the community (Dewi et al., 2021).

Although existing research results have shown the benefits of probiotics on gastrointestinal health, there are several limitations that need to be considered. First, most of the studies are observational or small-scale with limited populations, so generalisation of the results still requires caution. Secondly, not many studies have evaluated the long-term effects of traditional fermented food-based probiotic consumption in a large population. Thirdly, inter-individual variability in response to probiotics is still not fully understood, including the influence of genetics, baseline health status, and daily diet.

Future research should focus on multi-omics approaches to better understand the interaction of probiotics with the host microbiota and immune system, including through metagenomic, metabolomic and transcriptomic analyses. Further research is also needed to identify potential local strains from Indonesian fermented foods and evaluate their effectiveness through controlled clinical trials. In addition, the development of local food-based synbiotic formulations and personalised probiotic consumption strategies based on individual microbiota profiles are promising research opportunities in optimising probiotic-based nutritional interventions.

CONCLUSIONS

This study concludes that probiotics play a key role in maintaining and improving the health of the human gastrointestinal tract through complex and interrelated mechanisms. Key findings suggest that probiotics not only serve as complementary agents in the therapy of gastrointestinal disorders, but also have potential as evidence-based preventive and therapeutic strategies in gastrointestinal health management.

Firstly, modulation of gut microbiota composition is achieved through ecological competition mechanisms, whereby probiotics compete with pathogenic microbes for nutrients and mucosal adhesion sites. This competition is effective in inhibiting the colonisation of harmful microorganisms and creating a more conducive environment for commensal microorganisms. Secondly, probiotics also strengthen intestinal barrier function through stimulation of protein production at tight junctions and increased mucus secretion by goblet cells, thereby strengthening mucosal integrity and preventing increased intestinal permeability (leaky gut). These effects are important in inhibiting the translocation of pathogenic bacteria and endotoxins into the systemic circulation.

Thirdly, probiotics show potential in immunomodulation, particularly through interaction with dendritic cells, activation of Toll-like receptors, and stimulation of regulatory T lymphocytes (Treg). Activation of signalling pathways such as NF-κB and production of anti-inflammatory cytokines such as IL-10 contribute to the reduction of local and systemic inflammation. These effects have major implications for the prevention and management of inflammatory bowel diseases and irritable bowel syndrome (IBS).

Overall, adequate probiotic consumption, whether in the form of supplements or traditional fermented foods such as tempeh, tape and yoghurt, can provide clear physiological benefits to the balance of the gut microbiota and mucosal immune system. However, inter-individual variability in response, limited long-term evidence and lack of localised molecular studies are challenges that need to be addressed in the future. Therefore, future research should focus on cross-omic understanding, exploration of local strains based on traditional foods, and personalised approaches to optimise the effectiveness of probiotics in maintaining gastrointestinal health.

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