Probiotics, Prebiotics and their Role in Shaping the Gut Microbial Ecosystem

Affaf Ahsan[1], Zainab Fatima[2], Rida Niaz[1], Muhammad Arslan Akram[3], Saleha Tahir[4,*] and Ayesha Waris[5]

[1]Department of Nutrition and Dietetics, the University of Faisalabad, Pakistan
[2]Department of Biotechnology, University of Agriculture Faisalabad, Pakistan
[3]National institute of food science and technology, University of Agriculture Faisalabad Pakistan
[4]Department of Parasitology, University of Agriculture Faisalabad Pakistan
[5]Department of Physiology, the University of Faisalabad, Pakistan
*Corresponding author: salehatahir999@gmail.com

Abstract

The gut microbial community plays a very significant role in influencing health of individuals by expressively impacting the rate of nutrition, by boosting the immune system and by in reaction to some syndromes. The microbial gut community is rich with probiotics that are the beneficial bacteria to support good health. Prebiotics and probiotics, both of these terms are highly connected with each other that standardize microbial conformation. Prebiotics helps the probiotics to grow and develop in a balance way. They provide food to probiotics and also the source of energy for body. Thus, a balance maintains in a good manner. However, any imbalance in the community of microbes lead to various metabolic disorders such as cardiovascular diseases, obesity or diabetes. Development of short chain fatty acids that come to existence with the establishment of bioreactors or fermentation, eliminate many anti-inflammatory conditions. However, it is extremely vital to deliberate the challenges that are associated with this such as strain specific effects and considering variability when taking these discoveries which highly spot the necessities for additional exploration to enhance their satisfying potentials.

Keywords: Gut microbiota, Probiotics, Prebiotics, Metabolic disorders, Fermentation, Strain specificity

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Introduction

1. Introduction to Gut Microbiota

The word “microbiota” refers to the whole population of microorganism that collectively resides at a particular location i.e. on human gut, throughout the intestinal tract. The microbial population does not only include bacteria but some species of yeast, archaea or protists play significance role in shaping up the microbial community (El-Enshasy & Yang, 2021). Population nearly involves trillions of microorganisms that make symbiotic relationship with one another and provide a lot of benefits to the individuals or infants (Hori et al., 2020). For instance, they are mainly involving in the regulating the homeostasis as well as boost up the immune system throughout the life (Dey et al., 2023). The gut microbial residents play role in proper maintaining the metabolites of metabolic pathway. These metabolic pathways suppress the depressive conditions (Radford-Smith & Anthony, 2023). However, there are many factors that influence the composition of microbiota like unhealthy diet, aging or experience with different medicine predominantly antibiotics (Zaib et al., 2024). The formation of these microbial colonies particularly begins to form with the time of birth and this process continues until any damage occur to them because of some internal or external fluctuations (Mazziotta et al., 2023). The development of microbial colonization in the gut primarily includes by the interaction of two important microbial class which builds up the major part of gut microbes known as Bacteroidetes and Firmicutes (Li et al., 2023). While the other microbes such as action-bacteria, proteo-bacteria or fuso-bacteria from the family of archaea construct the remaining portion of gut microbiota with interactions of some fungi (Álvarez et al., 2021). Symbiotic relationship of microbial gut community play key role in providing many benefits to the host body by providing them energy after breaking down food source (Yang et al., 2023). The gut microbial community is majorly famous as bioreactors because they ferment many sugars and then these sugars ultimately involve in the formation of different acids like acetic acid, fatty acids, butyric acids and many more (Tripathy et al., 2023). Formation of some bioactive compounds like vitamin K or some toxic compounds like trimethylamine, storing of lipids, is majorly linked with the functioning of microbial gut population. An imbalance in the working of gut microbes causes some severe diseases or syndromes (Weng et al., 2024). The major role is being involved with the contribution of probiotics and prebiotics which are the integral part of gut microbial community. Presence of these microorganism make the gut fresh and in good health (Yuldasheva et al., 2024). Further enhancements have been emerged with the role of prebiotics in increasing the efficacy of next generation probiotics. These probiotics have been proved highly beneficial in the working of gut microbes (Fei et al., 2023). Inflammatory bowel diseases which cause adverse effects has been treated with combined effects of probiotics and prebiotics shown in Figure

1 (Roy & Dhaneshwar, 2023). Scientists are being more in depth to finding the role of these symbiotic bacteria that also cause disease when exposed to certain circumstances and cause diseases in individuals (Lázaro et al., 2024). Food and drug administration have promised that some foods are available in market with the label of probiotics that have been added in food stuffs to increase the nutritional value and demand of such foods (Sanlier & Kocabas, 2023). The future needs some highly progressive therapies to treat cancer and such other immune diseases, so considering this the pro-pre biotic therapy has been systematized that is majorly utilize to treat immunocompromised patients shown in a 1 (Singh et al., 2023).

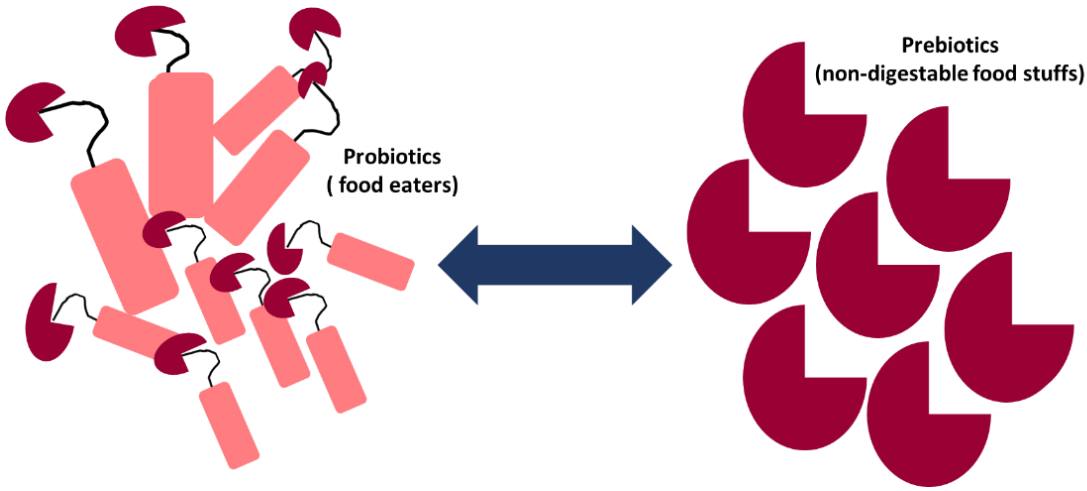

Fig. 1: Association between Probiotics and Prebiotics (Retrieved from BioRender)

Table 1: An Overview of Comparative analysis of prebiotics and probiotics with their interconnected benefits

Comparative analysis of prebiotics and probiotics with their interconnected benefits			
Characters	Probiotics	Prebiotics	References
Description	Beneficial microorganism that lives in the gut of humans.	Food stuffs of probiotics	(Lázaro et al., 2024).
Purpose	Build health of the individuals.	Boost immunity level	(Sanlier & Kocabas, 2023).
Sources	Milk, yogurt, curd	Grains, oats, mushrooms, seaweeds	(Singh et al., 2023).

2. Probiotics

Probiotics comprises of two main words pro and biotic which means before and life. Probiotics are the group of living beneficial microbes that provide extreme benefits to host by building healthy interaction with them (Kumar et al., 2020). Probiotics are found in the gut of individuals and play vital role in host by regulating the balance of microorganism that are available in intestine (Wang et al., 2021). The nourishment of gut microbial population starts developing from the time of birth and plays a very significant role in the long and short term health. There are various others factors that affect the shape of gut microbes and part of prebiotics is one from them (Beck et al., 2022). Recent researchers have reported that, availability of probiotics other than gut, they have also been found in the gut of some animals. There are many forms of products such as curd, yogurt or kafir which are produced by the combination of different probiotic species (Gomaa, 2020). Probiotics are useful bacteria that interact with host as well as with other advantageous microbial species. Some organisms prove very promising as probiotics for maintaining the gut community such as strains of *Lactobacillus, Bacillus, Streptococcus, E. coli, Saccharomyces* and *Enterococcus* (Zucko et al., 2020). Probiotics certainly impact the host by reducing the number of unhealthy bacteria that causes infections or diseases in the body shown in Figure 2 (Shahbazi et al., 2020). A recent report by world health organization has investigated the role of probiotics by treating many diseases such as diabetes, obesity or even cancer (Kothari et al., 2019). Probiotics majorly involved in the treating chronic diseases as well as in combating the effects of diabetes, obesity effects and cancer treatment (Badgeley et al., 2021). Probiotics marketplace is one of the profligates' developing sections in the food manufacturing and they have major effect on the health of buyers and they are precisely planned for the targeted position (Wang et al., 2022). Other than that, probiotic bacteria have reported to decrease the level of depression (Judkins et al., 2020). Activators of probiotics execute enzymatic absorption of host composites such as bile salts and consumed xeno-biotic. Specificity or microbial effects which is associated with effectors demonstrates the way easy for the delivery of strain specific effects which are related to probiotics (Zhang et al., 2023).

2.1. Mechanism of Action of Probiotics

2.1.1. Adhesion to gut surface

Recently, it has been found that with some other major advantages, probiotics also play a key role in decreasing the effects of antimicrobial by modifying the activity of microbiota in the gut or even on some other organs. The attachment of microbes with the activity of some regulatory proteins or carbohydrates plays an important role (Mazziotta et al., 2023).

2.1.2. Colonization

Some reports have also acknowledged the prominent role of probiotics in eliminating the pathogenic species, contest with harmful bacteria for their own existence and in producing such toxins which are detrimental for unwanted species by the activity of colonization after which microbes rapidly divide and increase their number (Latif et al., 2023).

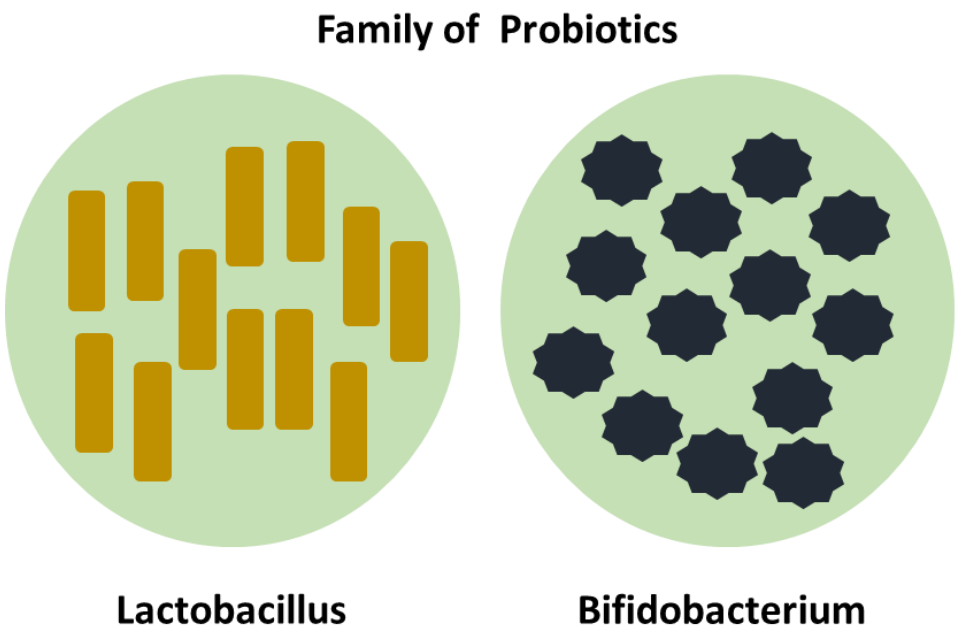

Fig. 2: Representation of bacterial species that are the source of Probiotics (Retrieved from BioRender)

2.1.3. Modulation of the gut Microbial Community

One of the significant actions of mechanism of probiotics is highly connected with the species of *Lactobacillus* from the source of lactic acid bacteria with the involvement of modulation. They usually reside on the gastrointestinal tract of the host, strongly attach to the surface of epithelium layer in the intestine and inhibit the growth of harmful bacteria that colonize on the tract such as species of *Salmonella* or *Shigella* (Huang et al., 2022). Presence of lactic bacterial species in the dietary product that are utilized by human provide intense immunity to the individual describe in Table 2. Mechanism of probiotics activity of lactic acid bacterial community to check that how these microbial species boost the immune level, was observed by inoculating the mouse with the species of *Lactobacillus*. Results showed the increased production of natural killer cells. Mouse's spleen cells were also dealt with *Lactobacillus* strains that generate higher amount of gamma interferons and also immobile the activity of toxic cells from being produced shown in Figure 3.

2.1.4. Generation of different Products in form of Metabolites

Another fine mechanism by probiotics is the production of some specific proteins, metabolites or other bioactive elements which are vital for processing in the body like keratin, fibrinogen and binding sites on mucosal surface, collagen binding or some elongation elements (Gul et al., 2024).

2.1.5. Prevention from Disorders Associated with Gut Issues

Diabetes majorly type 2 is related to metabolic illness which occur due to the hyperglycemia when pancreatic beta cells accommodate dis-functioning in the body and causes the resistance of insulin. New studies have revealed the effect that there is a connection in treating such diseases by enhancing the activity of gut microbiota that are concerned with metabolic syndromes, normalizing the gut brain axis and by soothing the function of epithelial blockades (Kobyliak et al., 2024).

2.1.6. Protection from Inflammatory Reactions and Balancing of Homeostasis

Probiotics therapeutic methodology has been widely approved worldwide because probiotics have shown auspicious results in treating inflammation and reducing the impact of disorders (Farooq, 2024). In the mechanism of action of probiotics, one of the most major specie other that *Lactobacillus* have been majorly involve called as *Streptococcus downii* demonstrates its valuable effect in oral intake of probiotic medicine which are also valuable for decreasing reactive species. Some medicines that are taken orally for treating ulcer effects widely involve the prescription of probiotics (Martínez et al., 2023). The probable mechanism of probiotics comprises anti-cancer motion, stopping and considering immune system associated infections and knock out the expansion of Alzheimer's disease and Huntington's disease (Pyo et al., 2024).

3. Prebiotics

Prebiotics are the care taker of probiotics which simply means that they play a vital role in maintaining the activity of microbiota of gut by providing them suitable conditions such as preservation of homeostasis. Such prebiotics are not involving any kind of bacteria but usually they are the materials such as some kind of nutrients stuffs that promote the development of probiotics (Hutkins et al., 2024). Sugars such as oligosaccharides are the most dominated form of prebiotics. Some other non-consumable sugars such as pectin or dextrin also included in the manner of prebiotics structure (Kennedy et al., 2023). Prebiotics while maintaining probiotics also promisingly effective for increasing the immunity, to protect from particular diseases and balancing the sugar and mineral composition (Bevilacqua et al., 2024). Because of its various advantages, they are widely used in food manufacturing industry as food additives, for example in the making of bread and dairy items, in the production of chocolate and candy stuffs and for the production of different enzymes (Ferreira et al., 2023). Poly-phenols or inulin which are

the form of prebiotics are particularly consumed by microbial gut community for emancipating short chain fatty acids compounds and many other secondary molecules which minimize the impact of toxic pH and also break the development of viruses (Ballan et al., 2020). Food departments have been highly concerned with the efficacy of prebiotics and given the name of dietary food to these outstanding substances. In the early times, it was thought that these dietary nutrients are not consumable sugars but has some functional features which make them superior on the base of their exceptional assistances. Later these dietary supplements were given the name of prebiotics (Ballini et al., 2023). The Codex Alimentarous Commission which is an organization developed by food authority for bringing great impact on the life of purchaser provided another definition of dietary food products that they are just single polymers that are combined and made sugar molecules such as carbohydrates. Those carbohydrates that are eat able should be consumed for better dietary product (Korkach et al., 2024). Activity of gut microbial community is being improved when probiotics consumes healthy food substances (Parkhomenko, 2023).

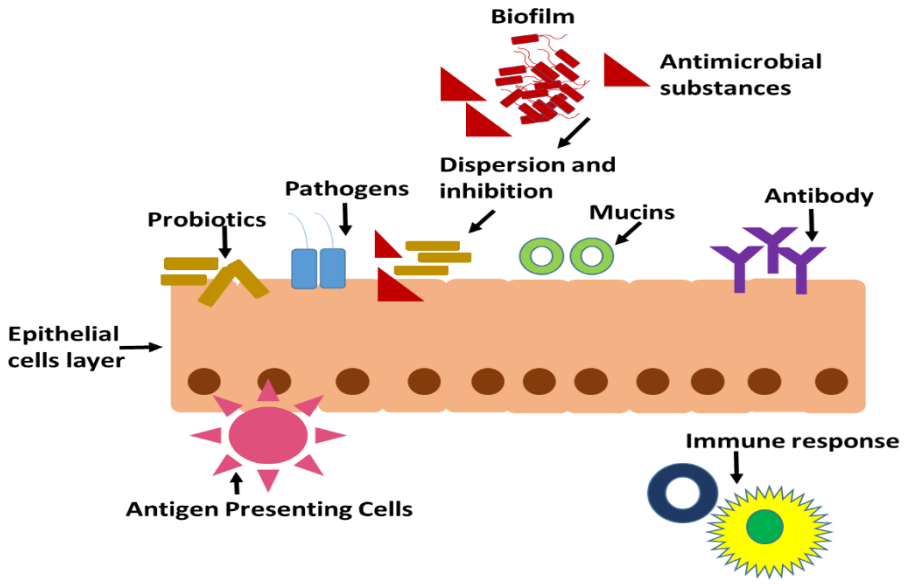

Fig. 3: Mechanism of Action of Probiotics (Retrieved from BioRender)

Table 2: Source of Probiotics and their Strains

Source of probiotics and their different strains		
Specie/strains	Sources	References
Lactobacillus acidophilus	Yogurt	(Roobab et al., 2020)
Bifidobacterium bifidum	Soybeans that have fermented	(Pyo et al., 2024)
Streptococcus thermophiles	Yogurt	(Martínez et al., 2023)
L. rhamnosus	Fermented milk	(Kobyliak et al., 2024)
Bifidobacterium lactis	Dairy stuffs	(Farooq, 2024)
L. planterum	Sauerkraut	(Huang et al., 2022)
Bacillus coagulans	Food stuff being fermented	(Wang et al., 2022)
L. casei	Fermented milk	(Wang et al., 2021)
Bifidobacterium breve	Soybeans after fermentation	(Gul et al., 2024)
Saccharomyces boulardii	Fermented yeast	(Mazziotta et al., 2023)

3.1. Mechanism of Action of Prebiotics

3.1.1. Selective Fermentation

The process of prebiotics starts with the process of selective fermentation i.e. bioreactors in which the non-consumable food stuffs stretch out to the site of colon and being provoked by healthy bacteria (Kango & Nath, 2024). This selection is considered a most vital phase because it allows prebiotics to bypass digestion in the GI tract and placed them away from colon so that they can be easily fermented with the help of effective microbial species (Kanwal et al., 2023). The bacterial species such as *Bifidobacterium* are majorly involved in breaking down these food stuffs and release energy. The energy that is generated is being utilized by microbial species for the process of fermentation (Limketkai et al., 2024). Microbes not only involve in energy utilization but this energy also support their health and helpful in growth, which eventually clues to the stable and healthy gut microbial community (Zeng et al., 2023).

3.1.2. Development of Short Chain Fatty Acids

After the fermented products, the formation of short chain fatty acids comes in interaction. These short chains are formed by the combination of six atoms of carbon that have been produced through anaerobic fermentation of prebiotic activity (Jeong et al., 2023). The short chains are majorly involving acetate, propionate or butyrate which are the source of energy on colonocytes, which are the sites for colon. The role of butyrate is widely concerned with the role colonocytes. Short chain fatty acids provide so many advantageous such as they standardize the pH, they moderate the immune health as well as they give antimicrobial effects which equalize the machinery of gut (Fusco et al., 2023).

3.1.3. Modulation of gut Microbes

The formation of shirt chain fatty acids further leads to variation in which prebiotics encourage the progression and action of microorganism such as *Bifidobacterium* which are essential in eliminating the impact of detrimental microbes (Ragavan & Hemalatha, 2024). In this way, the community of microorganism increase more in number and this increasing community is helpful in eradicating harmful metabolites and support valuable microbes in the gut (Huang et al., 2023). The variety of microbial gut community progress the gut barricade role.

3.1.4. Maintenance of Immune System

Prebiotics widely involve in providing strength to tight junction proteins as well as prevent the leakage of harmful microbes being enter into bloodstream (Song et al., 2023). So enhanced machinery of prebiotics helps to promote immune health and increase the level of immunity. This boosted level of immunity provides many health benefits to individual describe in Table 3 (Yoo et al., 2024). Healthy prebiotics protect people from chronic illness such as cancer and diabetes type 2. Other than that, prebiotics also reduce the effects of autoimmune diseases. Overall health of individual is being connected with the activity of prebiotics shown in Figure 4 (Törős et al., 2023).

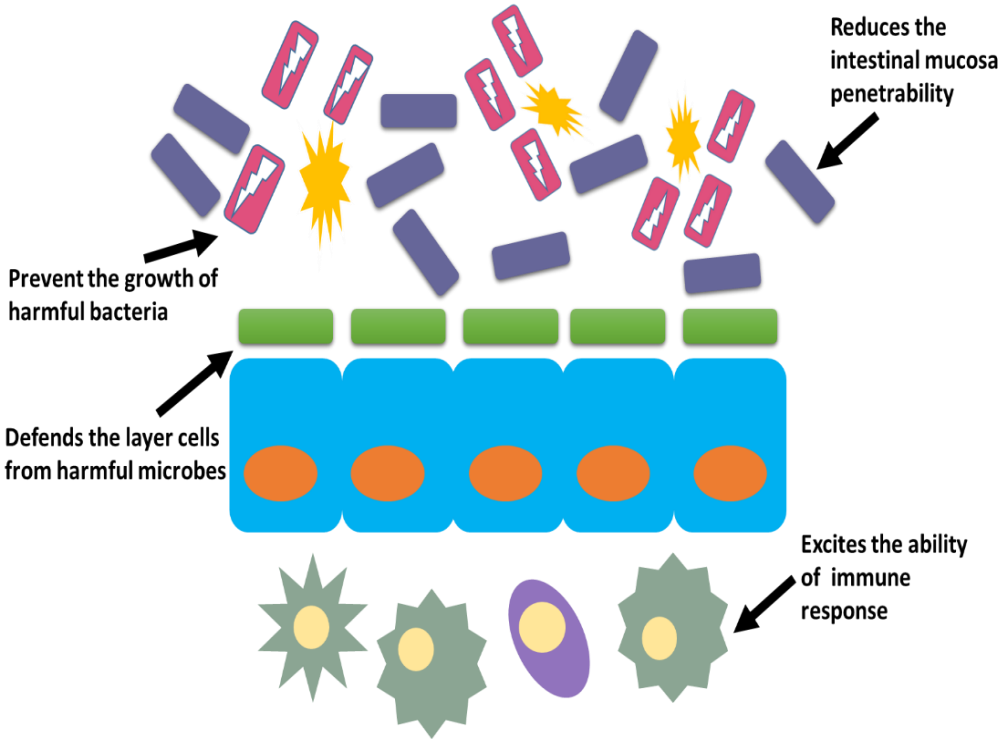

Fig. 4: Mechanism of Action of Prebiotics (Retrieved from BioRender)

Table 3: Sources of Prebiotics and their Health Benefits

Sources of prebiotics and their health benefits		
Source	Benefit	References
Banana	Important for health gut stability	(Gouda et al., 2022)
Asparagus	Proves a good source of digestion	(Törős et al., 2023)
Onion	Beneficial for immune health	(Yoo et al., 2024)
Bread	Aid proper digestion	(Jeong et al., 2023)
Garlic	Significant for heart issues	(Limketkai et al., 2024)
Apple	Boost muscles strengthen	(Zeng et al., 2023)
Barley	Removes anxiety	(Kango & Nath, 2024)
Oats	Knock out some stress conditions	(Ragavan & Hemalatha, 2024)

4. Communication between Prebiotics and Probiotics

The concept of common understanding between the operative functioning of probiotics and prebiotics have been investigated and in terms to keep overall healthy environment of the body, it is crucial to understand the interaction between prebiotics and probiotics (Sikorska-Zimny & Beneduce, 2021). The communication between probiotics and prebiotics is based on the concept of symbiosis but if its relationship does not work by mutual understanding then it is known as dysbiosis (Dahal et al., 2023). Symbiotic relationship is that when two organisms work by communal mechanism to run proper function without happening any kind of loss while dysbiosis is opposite to that concept. So, GI tract which is rich with symbiotic microbes provides many benefits to individuals. Their working is grounded on the conception that gut community gain so many nutrients from host but what these microbes return to the host? The answer to this simple question is that microorganism also break those nutritional stuff and provide them with a lot of energy (Leach, 2024). In this way the host remain fit and healthy and no harm reach to

them. If any damage occurs to symbiotic relationship, then it means that host facing some serious issues (Garvey, 2023). There are many diseases that are related with the dysbiosis like tumor. Childs face growth and height issues. However, there is a need to analyzed such situations at an early stage of growing life cycles so that damage can be handled. So, interaction between host and microbes remain stable when prebiotics and probiotics remain in touch with each other that are described in Table 4 (Mercer & Arrieta, 2023).

Table 4: Combined effects of Probiotics and Prebiotics on the Health of Individuals

Combined effects of probiotics and prebiotics on the health of individuals			
Probiotic	Prebiotic	Treatment	References
L. acidophilus	Inulin	Treat diabetes type 2	(Garvey, 2023)
Bifidobacterium bifidum	Polysaccharides	Recover from bowel syndrome	(Leach, 2024)
S. thermophiles	Oligosaccharides	Relief from diarrhea	(Dahal et al., 2023)
L. rhamnosus	Monosaccharides	Prevent cardiovascular diseases	(Sikorska-Zimny & Beneduce, 2021)
B. lactis	Mushrooms	stop autoimmune diseases	(Fusco et al., 2023)
L. planterum	Oats	Inhibit early birth problems	(Mercer & Arrieta, 2023)
B. coagulans	Berries	Avoid obesity	(Yoo et al., 2024)

5. Combined role of Probiotics and Prebiotics in Disease Management

Prebiotics and probiotics played an important role in maintaining those disorders that are related to gut such as bowel diseases, pain in abdomen or bloating. Their role also clears in minimizing inflammation and in improvement of conditions like ulcers. Their relation together can also prevent from attacking of harmful bacteria (Palai et al., 2020). Efficiency of pre-probiotics substantiates promising in treating immune system diseases (Lee et al., 2024). Major role of this symbiotic relationship while managing diseases in balancing diabetes and obesity that are important parameters of metabolic pathways (Manzoor et al., 2022). Modulation of gut by prebiotic substances and probiotics microbes are very prominent in giving assistance from anxiety and depression, so they have shown positive impact in treating diseases and disorders (Paiva et al., 2020).

6. Future Prospects and Current Challenges Related to Probiotics and Prebiotics

6.1. Challenges in Probiotics

There are variety of challenges that are associated with the strains of probiotics and they have detrimental effects on human health. Specificity of strain is one of the biggest challenges that has been faced. Proper dosage and duration is still lacking and need to be known (Aleixandre et al., 2020). These bacteria are sensitive to any change that occur in due to environmental variation, therefore more examination is necessary to govern the most suitable contingents which can also affect their viability and reliability. A proper Regulatory framework is significant in such regard (Trush et al., 2020).

6.2. Challenges in Prebiotics

Prebiotics are the nutrients for gut bacteria; there exact nutritive factors are not understandable until proper research is conducted on them. Interaction with dosage of probiotics is sufficient. Normalization of prebiotics are developing to launch a strong policy for marketing approaches (Pimentel et al., 2022).

6.3. Current Trends

Future is heavily dependent on the extreme use of probiotics and prebiotics effectiveness because they are important in assessing risks. With the progression in biotechnological techniques like genetic engineering and microbiota exploration, personalized probiotic tailor-made to every single person with their particular requirements have turn into an authenticity. Recent researches on the use of tailored probiotics are broadly evolving (Zang et al., 2024). Scientific officers are reconnoitering new bases for prebiotics such as new plants like mushrooms, seaweeds and other plant constructed materials. For future, there is more demand for developing Prebiotics substances that may be used to modulate the immune system and prevent tumor related disorders (Hasnain et al., 2024).

Conclusion

Probiotics and prebiotics are the interrelated terms that have gained significant status in recent years due to their impending to stimulate health of individuals and safety. Probiotics only work well when prebiotics are available in maximum amount. So, the link between these two components is essential for maintaining the microbiota. With the increasing benefits of this relationship such as enhancement of immune system, stress out from various diseases and some other disorders, there are also some challenges that are faced in some circumstances when these microbes are exposed to any other pressure. However, future of these pro-prebiotic evidences beneficial with significant applications in numerous fields

References

Aleixandre-Tudó, J. L., Castelló-Cogollos, L., Aleixandre, J. L., & Aleixandre-Benavent, R. (2020). Tendencies and challenges in worldwide scientific research on probiotics. *Probiotics and Antimicrobial Proteins*, 12, 785-797. https://doi.org/10.1007/s12602-019-09591-0

Álvarez, J., Real, J. M. F., Guarner, F., Gueimonde, M., Rodríguez, J. M., de Pipaon, M. S., & Sanz, Y. (2021). Gut microbes and health. *Gastroenterología y Hepatología* (English Edition), 44(7), 519-535. https://doi.org/10.1016/j.gastre.2021.01.002

Badgeley, A., Anwar, H., Modi, K., Murphy, P., & Lakshmikuttyamma, A. (2021). Effect of probiotics and gut microbiota on anti-cancer drugs:

Mechanistic perspectives. *Biochimica et Biophysica Acta (BBA)-Reviews on Cancer*, 1875(1), 188494. https://doi.org/10.1016/j.bbcan.2020.188494

Ballan, R., Battistini, C., Xavier-Santos, D., & Saad, S. M. I. (2020). Interactions of probiotics and prebiotics with the gut microbiota. *Progress in Molecular Biology and Translational Science*, 171, 265-300. https://doi.org/10.1016/bs.pmbts.2020.03.008

Ballini, A., Charitos, I. A., Cantore, S., Topi, S., Bottalico, L., & Santacroce, L. (2023). About functional foods: The probiotics and prebiotics state of art. *Antibiotics*, 12(4), 635. https://doi.org/10.3390/antibiotics12040635

Beck, L. C., Masi, A. C., Young, G. R., Vatanen, T., Lamb, C. A., Smith, R., & Stewart, C. J. (2022). Strain-specific impacts of probiotics are a significant driver of gut microbiome development in very preterm infants. *Nature Microbiology*, 7(10), 1525-1535. https://doi.org/10.1038/s41564-022-01213-w.

Bevilacqua, A., Campaniello, D., Speranza, B., Racioppo, A., Sinigaglia, M., & Corbo, M. R. (2024). An Update on Prebiotics and on Their Health Effects. *Foods*, 13(3), 446. https://doi.org/10.3390/foods13030446

Dahal, R. H., Kim, S., Kim, Y. K., Kim, E. S., & Kim, J. (2023). Insight into gut dysbiosis of patients with inflammatory bowel disease and ischemic colitis. *Frontiers in Microbiology*, 14, 1174832. https://doi.org/10.3389/fmicb.2023.1174832

Dey, P., Mukherjee, S. K., & Parai, D. (2023). Association of Probiotics and Prebiotics with Human Microbiome and the Functioning of Immune System. In Probiotics, Prebiotics, Synbiotics, and Postbiotics: Human Microbiome and Human Health (pp. 101-115). *Singapore: Springer Nature Singapore*. https://doi.org/10.1007/978-981-99-1463-0_6

El-Enshasy, H. A., & Yang, S. T. (2021). Probiotics, the Natural Microbiota in Living Organisms. *Probiotics, the Natural Microbiota in Living Organisms (1st ed.). CRC Press*. https://doi. org/10.1201/9781351027540.

Farooq, S. (2024). A review on pharmacokinetics, mechanism of action and side effects of probiotics. *International Journal of Molecular Microbiology*, 7(1), 39-59.

Fei, Y., Chen, Z., Han, S., Zhang, S., Zhang, T., Lu, Y., & Yao, M. (2023). Role of prebiotics in enhancing the function of next-generation probiotics in gut microbiota. *Critical Reviews in Food Science and Nutrition,* 63(8), 1037-1054.

Ferreira, V. C., Barroso, T. L. C. T., Castro, L. E. N., Da Rosa, R. G., & de Siqueira Oliveira, L. (2023). An overview of prebiotics and their applications in the food industry. *European Food Research and Technology*, 249(11), 2957-2976. https://doi.org/10.1007/s00217-023-04341-7

Fusco, W., Lorenzo, M. B., Cintoni, M., Porcari, S., Rinninella, E., Kaitsas, F., & Ianiro, G. (2023). Short-chain fatty-acid-producing bacteria: key components of the human gut microbiota. *Nutrients*, 15(9), 2211. https://doi.org/10.3390/nu15092211

Garvey, M. (2023). The association between dysbiosis and neurological conditions often manifesting with chronic pain. *Biomedicines*, 11(3), 748. https://doi.org/10.3390/biomedicines11030748

Gomaa, E. Z. (2020). Human gut microbiota/microbiome in health and diseases: a review. *Antonie Van Leeuwenhoek*, 113(12), 2019-2040. https://doi.org/10.1007/s10482-020-01474-7

Gouda, M., Tadda, M. A., Zhao, Y., Farmanullah, F., Chu, B., Li, X., & He, Y. (2022). Microalgae bioactive carbohydrates as a novel sustainable and eco-friendly source of prebiotics: emerging health functionality and recent technologies for extraction and detection. *Frontiers in Nutrition*, 9, 806692. https://doi.org/10.3389/fnut.2022.806692

Gul, S., Sattar, A., Akram, A., Waheed, A., Islam, M., Latif, U., & Muzammil, I. (2024). Harnessing the Power of Probiotics and Prebiotics: A Comprehensive Guide to Gut Health and Beyond. *Complementary and Alternative Medicine: Prebiotics and Probiotics*, 253-260. https://doi.org/10.47278/book.CAM/2024.417

Hasnain, M. A., Kang, D. K., & Moon, G. S. (2024). Research trends of next generation probiotics. *Food Science and Biotechnology*, 33(9), 2111-2121. https://doi.org/10.1007/s10068-024-01626-9

Hori, T., Matsuda, K., & Oishi, K. (2020). Probiotics: A dietary factor to modulate the gut microbiome, host immune system, and gut–brain interaction. *Microorganisms*, 8(9), 1401. https://doi.org/10.3390/microorganisms8091401

Huang, R., Wu, F., Zhou, Q., Wei, W., Yue, J., Xiao, B., & Luo, Z. (2022). Lactobacillus and intestinal diseases: Mechanisms of action and clinical applications. *Microbiological Research*, 260, 127019. https://doi.org/10.1016/j.micres.2022.127019

Huang, S. C., He, Y. F., Chen, P., Liu, K. L., & Shaukat, A. (2023). Gut microbiota as a target in the bone health of livestock and poultry: roles of short-chain fatty acids. *Animal Diseases*, 3(1), 23. https://doi.org/10.1186/s44149-023-00089-5

Hutkins, R., Walter, J., Gibson, G. R., Bedu-Ferrari, C., Scott, K., Tancredi, D. J., & Sanders, M. E. (2024). Classifying compounds as prebiotics—scientific perspectives and recommendations. *Nature reviews Gastroenterology & Hepatology*, 1-17. https://doi.org/10.1038/s41575-024-00981-6.

Jeong, J. J., Ganesan, R., Jin, Y. J., Park, H. J., Min, B. H., Jeong, M. K., & Suk, K. T. (2023). Multi-strain probiotics alleviate loperamide-induced constipation by adjusting the microbiome, serotonin, and short-chain fatty acids in rats. *Frontiers in Microbiology*, 14, 1174968. https://doi.org/10.3389/fmicb.2023.1174968

Judkins, T. C., Archer, D. L., Kramer, D. C., & Solch, R. J. (2020). Probiotics, nutrition, and the small intestine. *Current Gastroenterology Reports*, 22(1), 1-8. https://doi.org/10.1007/s11894-019-0740-3

Kango, N., & Nath, S. (2024). Prebiotics, Probiotics and Postbiotics: The Changing Paradigm of Functional Foods. *Journal of Dietary Supplements*, 1-27. https://doi.org/10.1080/19390211.2024.2363199

Kanwal, F., Ren, D., Kanwal, W., Ding, M., Su, J., & Shang, X. (2023). The potential role of nondigestible Raffinose family oligosaccharides as prebiotics. *Glycobiology*, 33(4), 274-288. https://doi.org/10.1093/glycob/cwad015

Kennedy, J. M., De Silva, A., Walton, G. E., & Gibson, G. R. (2024). A review on the use of prebiotics in ulcerative colitis. *Trends in Microbiology*, *32*(5), 507-515.

Kobyliak, N., Khomenko, M., Falalyeyeva, T., Fedchenko, A., Savchuk, O., Tseyslyer, Y., & Ostapchenko, L. (2024). Probiotics for pancreatic β-

cell function: from possible mechanism of action to assessment of effectiveness. *Critical Reviews in Microbiology*, 50(5), 663-683. https://doi.org/10.1080/1040841X.2023.2257776

Korkach, H. V., Kotuzaki, O. M., Khvostenko, K. V., & Makarova, O. V. (2024). Probiotics and prebiotics–functional ingredients for the confectionery industry. *Journal of Chemistry and Technologies*, 32(1), 119-130. https://doi.org/10.15421/jchemtech.v32i1.296251.

Kothari, D., Patel, S., & Kim, S. K. (2019). Probiotic supplements might not be universally-effective and safe: A review. *Biomedicine & Pharmacotherapy*, 111, 537-547. https://doi.org/10.1016/B978-0-12-823733-5.00020-9

Kumar, R., Sood, U., Gupta, V., Singh, M., Scaria, J., & Lal, R. (2020). Recent advancements in the development of modern probiotics for restoring human gut microbiome dysbiosis. *Indian Journal of Microbiology*, 60, 12-25.

Latif, A., Shehzad, A., Niazi, S., Zahid, A., Ashraf, W., Iqbal, M. W., & Korma, S. A. (2023). Probiotics: Mechanism of action, health benefits and their application in food industries. *Frontiers in Microbiology*, 14, 1216674. https://doi.org/10.3389/fmicb.2023.1216674

Lázaro, Á., Vila-Donat, P., & Manyes, L. (2024). Emerging mycotoxins and preventive strategies related to gut microbiota changes: probiotics, prebiotics, and postbiotics–a systematic review. *Food & Function*. 10.1039/D4FO01705F

Leach, S. T. (2024). Role of probiotics and prebiotics in gut symbiosis. *Nutrients*, 16(2), 238. https://doi.org/10.3390/nu16020238

Lee, S., Choi, S. P., Choi, H. J., Jeong, H., & Park, Y. S. (2024). A comprehensive review of synbiotics: an emerging paradigm in health promotion and disease management. *World Journal of Microbiology and Biotechnology*, 40(9), 280. https://doi.org/10.1007/s11274-024-04085-w

Li, H., Liu, T., Zhang, X., Xiong, Z., Hong, Q., Jia, S., & Zhao, Y. (2023). Whole-genome sequencing and bacteriocin purification of Lactiplantibacillus plantarum HY41 confirms bactericidal and probiotic potential. *International Biodeterioration & Biodegradation*, 185, 105685. https://doi.org/10.1016/j.ibiod.2023.105685

Limketkai, B. N., Godoy-Brewer, G., Shah, N. D., Maas, L., White, J., Parian, A. M., & Mullin, G. E. (2024). Prebiotics for Induction and Maintenance of Remission in Inflammatory Bowel Disease: Systematic Review and Meta-Analysis. *Inflammatory Bowel Diseases*, izae115. https://doi.org/10.1093/ibd/izae115

Manzoor, S., Wani, S. M., Mir, S. A., & Rizwan, D. (2022). Role of probiotics and prebiotics in mitigation of different diseases. *Nutrition*, 96, 111602. https://doi.org/10.1016/j.nut.2022.111602

Martínez-Lamas, L., García-Mato, E., Rincón-Quintero, A., Rivas-Mundiña, B., Diz-Dios, P., & Álvarez-Fernández, M. (2023). Mechanism of Action of Streptococcus downii, a New Bacterial Species with Probiotic Potential. *Antibiotics*, 12(9), 1472. https://doi.org/10.3390/antibiotics12091472

Mazziotta, C., Tognon, M., Martini, F., Torreggiani, E., & Rotondo, J. C. (2023). Probiotics mechanism of action on immune cells and beneficial effects on human health. *Cells*, *12*(1), 184. https://doi.org/10.3390/cells12010184

Mercer, E. M., & Arrieta, M. C. (2023). Probiotics to improve the gut microbiome in premature infants: are we there yet?. *Gut Microbes*, 15(1), 2201160. https://doi.org/10.1080/19490976.2023.2201160

Paiva, I. H. R., Duarte-Silva, E., & Peixoto, C. A. (2020). The role of prebiotics in cognition, anxiety, and depression. *European Neuropsychopharmacology*, 34, 1-18. https://doi.org/10.1016/j.euroneuro.2020.03.006

Palai, S., Derecho, C. M. P., Kesh, S. S., Egbuna, C., & Onyeike, P. C. (2020). Prebiotics, probiotics, synbiotics and its importance in the management of diseases. *Functional Foods and Nutraceuticals: Bioactive Components, Formulations and Innovations*, 173-196. https://doi.org/10.1007/978-3-030-42319-3_10

Parkhomenko, A. (2023). Front-of-Pack Nutrition Labelling: are Health Policy Decisions Reconcilable with the WTO Disciplines?. Zhurnal VSHÉ po mezhdunarodnomu pravu (HSE University *Journal of International Law*), 1(2), 95-112. https://doi.org/10.17323/jil.2023.18198

Pimentel, T. C., de Assis, B. B. T., dos Santos Rocha, C., Marcolino, V. A., Rosset, M., & Magnani, M. (2022). Prebiotics in non-dairy products: Technological and physiological functionality, challenges, and perspectives. *Food Bioscience*, 46, 101585. https://doi.org/10.1016/j.fbio.2022.101585

Pyo, Y., Kwon, K. H., & Jung, Y. J. (2024). Probiotic functions in fermented foods: anti-viral, immunomodulatory, and anti-cancer benefits. *Foods*, 13(15), 2386. 10.3390/foods13152386

Radford-Smith, D. E., & Anthony, D. C. (2023). Prebiotic and probiotic modulation of the microbiota–gut–brain axis in depression. *Nutrients*, 15(8), 1880. https://doi.org/10.3390/nu15081880

Ragavan, M. L., & Hemalatha, S. (2024). The functional roles of short chain fatty acids as postbiotics in human gut: future perspectives. *Food Science and Biotechnology,* 33(2), 275-285. https://doi.org/10.1007/s10068-023-01414-x

Roobab, U., Batool, Z., Manzoor, M. F., Shabbir, M. A., Khan, M. R., & Aadil, R. M. (2020). Sources, formulations, advanced delivery and health benefits of probiotics. *Current Opinion in Food Science*, 32, 17-28. https://doi.org/10.1016/j.cofs.2020.01.003

Roy, S., & Dhaneshwar, S. (2023). Role of prebiotics, probiotics and synbiotics in management of inflammatory bowel disease: Current perspectives. *World Journal of Gastroenterology*, 29(14), 2078. 10.3748/wjg.v29.i14.2078

Sanlier, N., & Kocabas, Ş. (2023). The effect of probiotic, prebiotic and gut microbiota on ASD: a review and future perspectives. *Critical Reviews in Food Science and Nutrition*, 63(15), 2319-2330. https://doi.org/10.1080/10408398.2021.1973957

Shahbazi, R., Yasavoli-Sharahi, H., Alsadi, N., Ismail, N., & Matar, C. (2020). Probiotics in treatment of viral respiratory infections and neuroinflammatory disorders. *Molecules*, 25(21), 4891. https://doi.org/10.3390/molecules25214891

Sikorska-Zimny, K., & Beneduce, L. (2021). The metabolism of glucosinolates by gut microbiota. *Nutrients*, 13(8), 2750 https://doi.org/10.3390/nu13082750

Singh, A., Alexander, S. G., & Martin, S. (2023). Gut microbiome homeostasis and the future of probiotics in cancer immunotherapy. *Frontiers in Immunology*, 14, 1114499. https://doi.org/10.3389/fimmu.2023.1114499

Song, M., Zhang, Z., Li, Y., Xiang, Y., & Li, C. (2023). Midgut microbiota affects the intestinal barrier by producing short-chain fatty acids in Apostichopus japonicus. *Frontiers in Microbiology*, 14, 1263731. https://doi.org/10.3389/fmicb.2023.1263731

Törős, G., El-Ramady, H., Prokisch, J., Velasco, F., Llanaj, X., Nguyen, D. H., & Peles, F. (2023). Modulation of the gut microbiota with prebiotics and antimicrobial agents from Pleurotus ostreatus mushroom. *Foods*, 12(10), 2010. https://doi.org/10.3390/foods12102010

Tripathy, S., Patel, A. R., Verma, D. K., Singh, S., Utama, G. L., Thakur, M., & Aguilar, C. N. (2023). Strategies, Trends, and Technological Advancements in Microbial Bioreactor System for Probiotic Products. *Microbial Bioreactors for Industrial Molecules*, 443-463. https://doi.org/10.1002/9781119874096.ch21

Trush, E. A., Poluektova, E. A., Beniashvilli, A. G., Shifrin, O. S., Poluektov, Y. M., & Ivashkin, V. T. (2020). The evolution of human probiotics: challenges and prospects. *Probiotics and Antimicrobial Proteins*, 12, 1291-1299. https://doi.org/10.1007/s12602-019-09628-4

Wang, G., Chen, Y., Xia, Y., Song, X., & Ai, L. (2022). Characteristics of probiotic preparations and their applications. *Foods*, 11(16), 2472. https://doi.org/10.3390/foods11162472

Wang, X., Zhang, P., & Zhang, X. (2021). Probiotics regulate gut microbiota: an effective method to improve immunity. *Molecules*, 26(19), 6076. https://doi.org/10.3390/molecules26196076

Weng, C. Y., Suarez, C. C., Kalanetra, K. M., Blecksmith, S. M., Lemay, D. M., Mills, D. A., & Lebrilla, C. B. (2024). A Targeted Multi-Omics Platform for Characterizing Prebiotic-Probiotic Interactions. *Current Developments in Nutrition*, 8, 103498.

Yang, J., Yang, H., & Li, Y. (2023). The triple interactions between gut microbiota, mycobiota and host immunity. *Critical Reviews in Food Science and Nutrition*, 63(33), 11604-11624. https://doi.org/10.1080/10408398.2022.2094888

Yoo, S., Jung, S. C., Kwak, K., & Kim, J. S. (2024). The Role of Prebiotics in Modulating Gut Microbiota: Implications for Human Health. *International Journal of Molecular Sciences*, 25(9), 4834. https://doi.org/10.3390/ijms25094834

Yuldasheva, M., Narziev, B., Mamatova, Z., Khaydarova, S., & Shomakhsudov, A. (2024). Effect of probiotic bacteria of the genus Bacillus on gnorobic pathogens of surgical infections. In BIO Web of Conference, *EDP Sciences* (Vol. 95, p. 01033). https://doi.org/10.1051/bioconf/20249501033

Zaib, S., Hayat, A., & Khan, I. (2024). Probiotics and their beneficial health effects. *Mini Reviews in Medicinal Chemistry,* 24(1), 110-125. https://doi.org/10.2174/1389557523666230608163823

Zang, T., Han, L., Lu, Z., Tan, L., Liang, D., Shen, X., & Sun, J. (2024). The history and prediction of prebiotics and postbiotics: a patent analysis. *Nutrients*, 16(3), 380. https://doi.org/10.3390/nu16030380

Zeng, M., Li, N., Astmann, T., Oh, J. H., van Pijkeren, J. P., & Pan, X. (2023). Facile and efficient chemical synthesis of gluco-oligosaccharides (GlcOS) with diverse glycosidic linkages as potential prebiotics to promote the growth of probiotic bacteria. *Food Research International,* 165, 112436. https://doi.org/10.1016/j.foodres.2022.112436

Zhang, D., Jian, Y. P., Zhang, Y. N., Li, Y., Gu, L. T., Sun, H. H., & Xu, Z. X. (2023). Short-chain fatty acids in diseases. *Cell Communication and Signaling,* 21(1), 212. 10.1016/j.tim.2021.01.003

Zucko, J., Starcevic, A., Diminic, J., Oros, D., Mortazavian, A. M., & Putnik, P. (2020). Probiotic–friend or foe?. *Current Opinion in Food Science*, 32, 45-49. https://doi.org/10.1016/j.cofs.2020.01.007