THE IMPACT OF PROBIOTICS ON ANIMAL HEALTH

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1. The Impact of Probiotics on Animal Health

Microorganisms are ubiquitous living systems harbored in all sections and anatomic districts of the animal body. Nevertheless, microbial communities associated to the gastrointestinal tract (GIT) are nowadays accounted as the most abundant and biodiverse, and their massive featuring highlighted concern in many physiological processes of most superior animals, humans included. In this light, the focus of the present chapter is GIT-associated microbial communities and the functional assets they are associated with, although pivotal roles and potentials are recognized to the microbial communities inhabiting other anatomical districts (Deusch, Tilocca, Camarinha-Silva, & Seifert, 2015).

In recent years, the use of probiotics in animal health has garnered significant attention and interest among researchers, veterinarians, and animal owners alike. Probiotics, defined as live microorganisms that confer health benefits when administered in adequate amounts, have shown promising results in enhancing the well-being and performance of various animal species. Primarily consist of beneficial bacteria and yeast strains, such as Lactobacillus spp., Bifidobacterium spp., and Saccharomyces spp., among others (Abd El-Hack et al., 2022; Abdelbasir, McCourt, Lee, & Vanegas, 2020).

GIT microorganisms are naturally present in all animals and play crucial roles in maintaining gut health and immune function. However, factors such as stress, illness, or antibiotic use can disrupt the balance of these microbial communities, leading to digestive disorders, reduced nutrient absorption, and susceptibility to infections. In this scenario, modulating the microbial community through administration of probiotics counterbalance the above dysbiosis conditions laying at the ground of the insurgence and/or progression of system pathologies of both infective and noninfective origin (Colditz & Hine, 2016; Committee et al., 2018).

The following chapter provides an overview of the usage of probiotics to sustain animal health and production in diverse zootechnic contexts.

2. Mechanisms of Action of Probiotics

The mechanisms through which probiotics exert their beneficial effects on animals are multiple and intricated (Figure1). They competitively exclude harmful pathogens by occupying binding sites on the intestinal epithelium, thereby preventing the colonization of pathogens. Also, probiotics enhance the integrity of the gut mucosal barrier by promoting the production of mucins and strengthening tight junctions between epithelial cells. Probiotics help prevent the translocation of pathogens and toxins across the intestinal lining. This barrier function is crucial for maintaining immune homeostasis which is, as well, modulated by the metabolic activity of probiotics strains.

Altogether probiotics' mechanisms reduce the risk of gastrointestinal infections and improve overall health.

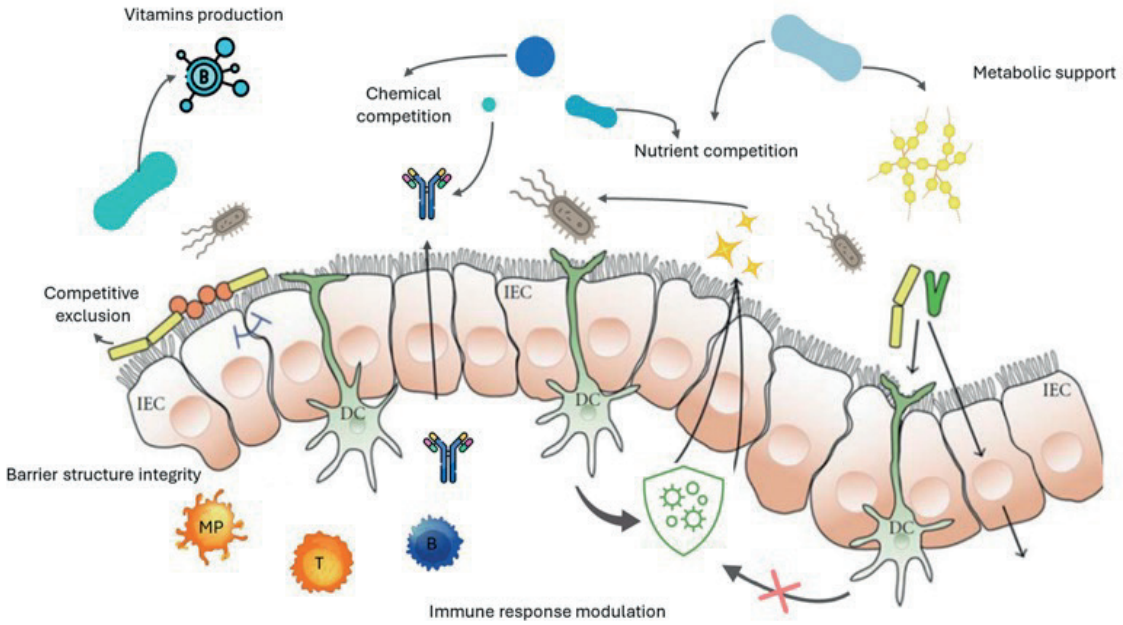


Figure 1. Mechanisms of action of probiotics. The figure summarizes the major mechanisms undertaken by the probiotic's cells administered to support animal health status. IEC: intestinal epithelial cells; DC: dendritic cells; MP: macrophages; T: T-cell lymphocyte; B: B-cell lymphocyte.

2.1 Composition of the microbial community

The direct mechanism of action of probiotics includes the modulation of the microbial community composition within the gut. This involves establishing complex interactions between the probiotic microorganisms themselves, the indigenous gut microbiota, and the host's gastrointestinal environment. It impacts the alpha-microbial diversity, microbial richness and evenness (Maftei et al., 2024). These, in turn, are mirrored as altered patterns of interactions among the microorganisms and its host, accounting for both qualitative and quantitative changes, resulting in the ameliorated tuning of the physiological functions as mediated by the hosted microbial community (Celi et al., 2017). In addition, probiotics stimulate the production of mucins, which are glycoproteins that form the protective mucus layer covering the intestinal epithelium. Such mucus layer serves as a physical barrier against pathogens and toxins, while also providing a habitat for beneficial bacteria (Paone & Cani, 2020). By promoting mucus production and maintaining barrier function, probiotics support gastrointestinal health and reduce the risk of intestinal permeability and the associated inflammatory responses.

As of today, further research into the specific mechanisms and interactions involved in probiotic-mediated microbiota modulation helped, and will continue, to uncover new therapeutic potentials for managing a wide range of health conditions in both humans and animals.

2.2 Metabolic support of the microbial community

The metabolic activities of probiotics are diverse and multifaceted, impacting various aspects of host physiology and gut microbiota composition. Through fermentation, production of antimicrobial compounds, modulation of immune responses, enhancement of nutrient utilization, reduction of oxidative stress, and metabolism of bile acids, probiotics provide a significant contribution to the gut health, improving overall well-being in animals and humans alike (Santos-Buelga, González-Paramás, Oludemi, Ayuda-Durán, & González-Manzano, 2019; Sanz & De Palma, 2009).

2.2.1. Fermentation and Acidification

Probiotic bacteria are known for their ability to ferment various substrates present in the gut, such as dietary fibers and complex carbohydrates. During fermentation, probiotics produce short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These, in turn, lower the intestinal lumen pH, creating an acidic environment that inhibits the growth of pathogenic bacteria. In this manner, probiotics promote a favorable ecological niche for themselves and other beneficial microorganisms, besides suppressing harmful pathogens (Dakal, Kumar, Majumdar, & Yadav, 2016; Dama et al., 2024).

2.2.2. Production of Antimicrobial Compounds

Probiotics can synthesize and release antimicrobial substances that directly inhibit the growth of pathogenic bacteria. These antimicrobial compounds may include bacteriocins, hydrogen peroxide, organic acids, and peptides. Bacteriocins are proteinaceous toxins produced by probiotics that specifically target and kill even closely related bacterial strains without exerting the toxic effect on the beneficial ones. This chemical exclusion mechanism helps probiotics to maintain dominance and prevent colonization by harmful microbes in the gut. Analogously, other antimicrobial compounds produced by the probiotics strains exert their activity by other mechanisms including pore formation and enzyme activity modulation, as well as quorum sensing after having t

2.2.3. Modulation of Immune Response

The metabolic by-products of probiotics, particularly SCFAs like butyrate, have immunomodulatory properties. Butyrate, for example, serves as an energy source for colonic epithelial cells and helps to maintain intestinal barrier function. It also regulates the production of inflammatory cytokines and promotes the differentiation of regulatory T cells (Tregs), which play a key role in immune tolerance and homeostasis. By influencing the gut-associated lymphoid tissue (GALT) and mucosal immune responses, probiotics contribute to enhancing the host's immune defense against pathogens (Zhou, Chen, Patil, & Dong, 2024).

2.2.4. Enhancement of Nutrient Utilization

Probiotics can enzymatically break down complex nutrients that are otherwise indigestible by the host's digestive enzymes. For instance, specific strains of probiotics are employed to provide enzymes like cellulase and xylanase that degrade plant cell walls and release nutrients such as sugars and vitamins. This enzymatic activity enhances nutrient absorption and utilization by the host, leading to improved growth performance and feed efficiency in animals (Yi, Pan, Long, Tan, & Zhao, 2020).

2.2.5. Reduction of Oxidative Stress

Some probiotic strains possess antioxidant properties and can scavenge free radicals within the gut environment. By reducing oxidative stress, probiotics help protect intestinal cells from damage caused by reactive oxygen species (ROS), which are generated during normal metabolic processes and under conditions of inflammation or stress. This antioxidant activity contributes to maintaining gut barrier integrity and overall health status (Al-Shawi et al., 2020; Anadón, Ares, Martínez-Larrañaga, & Martínez, 2019).

2.2.6. Metabolism of Bile Acids and Cholesterol

Certain probiotics have the ability to metabolize bile acids, facilitating their excretion from the body. This metabolic activity can lower blood cholesterol levels by reducing the reabsorption of bile acids in the intestine, thereby promoting cardiovascular health. Additionally, probiotics may directly influence lipid metabolism and bile acid synthesis in the liver through signaling pathways involving SCFAs and other metabolic intermediates (Abd El-Hack et al., 2022; Abdelbasir et al.,

2020).

In summary, the mechanism of action of probiotics via their metabolic activity involves a complex interplay between the probiotic microorganisms and the host's gut environment. Probiotics exert their beneficial effects through a variety of metabolic activities; although, not all of them have yet been elucidated. Further research into the specific metabolic pathways and interactions between probiotics and host physiology will continue to unveil new therapeutic potentials and applications in

3. Probiotics Applications in Animal Health

The application of probiotics in animal health spans across various species, including livestock (such as cattle, poultry, and swine), companion animals (like dogs and cats), and even exotic animals kept in captivity. In livestock farming, probiotics have been extensively studied for their ability to improve growth performance, feed efficiency, and resistance to diseases.

3.1. Cattle

Probiotics can contribute to overall gut health in cows, promoting better digestion and absorption of nutrients. Probiotics support cow nutrition through various mechanisms. Ruminants rely on microbial fermentation in the rumen to break down fibrous plant material. Probiotics containing fiber-degrading bacteria such as Fibrobacter succinogenes and Ruminococcus flavefaciens showed enhanced metabolism of complex carbohydrates (cellulose and hemicellulose) into simpler sugar units that animals can absorb and utilize more efficiently. Here, probiotic strains, such as those belonging to the genus Lactobacillus and Bifidobacterium, resulted in improved protein digestion in the rumen. They produce enzymes that break down proteins into amino acids, which are then available for absorption and used for growth, milk production, and maintaining of the overall health status (El Jeni et al., 2023). Also, probiotics can improve the availability and absorption of minerals such as calcium, phosphorus, magnesium, and iron. For example, lactic acid bacteria and certain strains of Bacillus spp. produce organic acids that lower pH in the gut, facilitating the solubilization of minerals and their subsequent absorption (Varvara & Vodnar, 2023). Similarly, vitamins are produced by a variety of probiotic bacteria, mainly strains of Bifidobacterium and Lactobacillus. These have the ability to synthesize vitamins such as group-B vitamins (B1, B2, B6, B12) and vitamin K. These vitamins are crucial in various metabolic processes and overall health in cows (Wan et al., 2022).

Besides the production of nutritional components, probiotics are active in the degradation and/or neutralization of anti-nutritional factors naturally present in feed ingredients, such as phytates and tannins (Petrova et al., 2022). These, indeed, inhibit the absorption of minerals and reduce the digestibility of proteins and carbohydrates. By degrading these compounds, probiotics improve overall feed efficiency and nutrient utilization. Furthermore, a healthy gut microbiota, as promoted by probiotics, maintains intestinal integrity and function. This supports nutrient absorption, ensures that the gut lining is healthy, immunocompetent and capable of absorbing nutrients effectively.

In addition, probiotics actions extend to reducing the risk of infections associated with suboptimal nutrition or stress. Stress can compromise immune function in cows, making them more susceptible to infections. Probiotics have been shown to mitigate the negative effects of stress by modulating the gut-brain axis and supporting a healthy gut microbiota; in turn, enhances immune responses and resilience to infections (Binda et al., 2024).

Concerning the protective role of probiotics against infective agents, mastitis is an informative example. Worldwide, mastitis is common and among the costliest infection in dairy cows. Probiotics such as Lactobacillus spp. and Streptococcus spp. have been studied for their ability to counterbalance mastitis-causing pathogens like Staphylococcus aureus and Escherichia coli by preventing them from adhering to mammary epithelial cells (Bouchard et al., 2015). Also, selected probiotics strains can modulate the immune response in the udder, reducing the severity of mastitis (Kober et al., 2022).

Diarrheal diseases in calves can be caused by various pathogens such as rotavirus, coronavirus, and enterotoxigenic E. coli. Probiotics strains of Lactobacillus and Bifidobacterium scored an improved gut health and reduced incidence and severity of diarrhea by competing with pathogens for binding sites, production of antimicrobial substances, and enhancing mucosal barrier function (Kober et al., 2022).

Respiratory diseases such as bovine respiratory disease complex (BRDC) are of significant concerns in cattle. Oral administration of probiotics has proved to enhance immune responses in the respiratory tract; thus, reducing pathogen colonization and mitigating the severity of infections caused by bacteria like Mannheimia haemolytica and Pasteurella multocida (Andrés-Lasheras, Jelinski, Zaheer, & McAllister, 2022).

Altogether, by improving nutrient digestion and uptake, enhancing natural defenses and reducing the prevalence of pathogenic bacteria, probiotics administration in the cow industry help reduce the need for antibiotics in managing infections (Andrés-Lasheras et al., 2022). This approach supports sustainable farming practices and mitigates the risk of antibiotic resistance development.

3.2. Probiotics administration in the poultry industry

The poultry industry employs probiotics in farming practice acknowledged their ability to promote health status. Probiotic strains of Lactobacillus spp., Bifidobacterium spp., and Bacillus spp., colonize the avian intestinal tract and compete with harmful bacteria like Salmonella spp. and Clostridium perfringens, preventing system infections and the spread of foodborne diseases (Fathima, Shanmugasundaram, Adams, & Selvaraj, 2022). Immunomodulatory effects of probiotics have been documented in both innate and adaptive immune responses. They stimulate the production of immunoglobulins, enhance phagocytic activity of macrophages, and promote the proliferation and activation of T cells and natural killer (NK) cells in the GALT. This immune modulation helps chickens mount effective immune responses against pathogens, reduces the incidence of infections, and supports overall immune health and resilience.

In practical applications, probiotics are often administered through feed or water supplements to poultry flocks. This method is convenient and has shown promising results in field trials for reducing the incidence and severity of avian flu outbreaks. Also, probiotics hinder the shedding of avian flu viruses in poultry feces. This can lower the transmission of the virus within the flock and to other birds, thereby helping to control outbreaks (Parida, 2009).

Other applications of probiotics in the poultry industry include the control of Salmonella infections. Salmonellosis is a major concern in poultry due to its impact on both bird health and food safety. Probiotics, such as Lactobacillus and Bacillus, have been shown to competitively exclude Salmonella from the chicken gut colonization by means of both physical and chemical competition (Micciche, Foley, Pavlidis, McIntyre, & Ricke, 2018).

Clostridium perfringens is another impactful pathogen in the poultry sector as it can cause necrotic enteritis in chickens, leading to significant economic losses. Probiotics like Bacillus subtilis and other lactic acid bacteria have demonstrated the ability to inhibit Clostridium perfringens growth and reduce the incidence of necrotic enteritis when administered regularly in feed (Aljumaah et al., 2020). Analogously, Campylobacteriosis is a leading cause of foodborne illness associated with poultry products (Śmiałek, Kowalczyk, & Koncicki, 2021) . Probiotics have been investigated for their potential to reduce Campylobacter colonization in chickens. Studies have shown that selected probiotic strains can decrease Campylobacter counts in the chicken gut, thereby lowering the risk of contamination during processing (Śmiałek et al., 2021). The effectiveness of probiotics has been demonstrated also on parasites. Eimeria species are protozoan parasites responsible for coccidiosis. Administration of probiotics such as Saccharomyces cerevisiae and Bacillus spp. have been used to manage Eimeria infections by promoting gut health and enhancing immunity against coccidiosis (Kiarie, Leung, Akbari Moghaddam Kakhki, Patterson, & Barta, 2019).

Besides biotic insults, the poultry industry faces various stressors that can negatively impact bird health and productivity. Here, probiotics have been utilized to mitigate the negative effects of stress on chickens acquired during stressful conditions such as transportation, vaccination, or environmental changes. Administering probiotics can help maintain gut integrity, strengthen immune defenses, and improve overall resilience against infectious agents. In addition, as concerns over antibiotic resistance and consumer preferences for antibiotic-free poultry products grow, probiotics offer a viable alternative to antibiotic growth promoters (AGPs) in poultry production enabling growth performance and health without contributing to antibiotic resistance or residues in poultry meat and eggs (Kiarie et al., 2019).

Despite the numerous benefits of probiotics in poultry production, challenges remain, including the selection of appropriate probiotic strains, optimization of dosage and administration methods, and variability in efficacy under different farming conditions. Factors such as feed composition, management practices, and bird genetics can influence the effectiveness of probiotic supplementation in poultry. In this light, continued research into probiotic strains, formulations, and application strategies will further optimize their use for maximizing poultry health, welfare, and productivity globally.

3.3. Probiotics usage in pig productions

Probiotics have gained significant attention and application in the pig industry due to their potential to improve growth performance, feed efficiency, and overall health of pigs. One of the primary benefits of probiotics in pigs is their ability to promote gut health. Strains of Lactobacillus and Bifidobacterium, colonize the intestinal tract and compete with harmful bacteria for nutrients and attachment sites on the gut wall. This competitive exclusion reduces the proliferation of pathogens like Escherichia coli and Salmonella spp., thereby lowering the incidence of gastrointestinal infections and diarrhea in piglets (Attia et al., 2023). Also, probiotics help improve the digestive efficiency of pigs by enhancing the breakdown and absorption of nutrients from feed. They produce enzymes such as amylases, proteases, and cellulases that aid in the digestion of complex carbohydrates, proteins, and fibers. Facilitating nutrient utilization is crucial for optimizing growth rates and reducing production costs in pig farming (Canibe et al., 2022). Moreover, probiotics play a vital role in modulating the immune system of pigs. They stimulate the production of immunoglobulins and enhance the activity of immune cells such as macrophages and T cells in the gut-associated lymphoid tissue (GALT). This immune modulation helps pigs mount effective immune responses against pathogens and improves their resistance to infections and diseases, thereby reducing the need for antibiotic treatments. This positively impacts the marketability of the pig industry products. Indeed, with increasing regulatory restrictions and consumer concerns over antibiotic use in livestock production, probiotics offer a viable alternative to antibiotic growth promoters (AGPs). Probiotics provide similar growth-promoting effects by enhancing nutrient absorption, maintaining gut health, and boosting immune function without contributing to antibiotic resistance or residues in meat products. This shift towards probiotic supplementation aligns with sustainable and responsible farming practices in the pig industry (Liao & Nyachoti, 2017). In this view, the use of probiotics in pig farming has been associated with reduced stress levels and improved welfare outcomes. Stress factors such as weaning, transportation, and changes in diet can disrupt the gut microbiota and compromise immune function in pigs. Probiotics help maintain microbial balance, support gut barrier function, and mitigate stress-induced intestinal inflammation, thereby promoting overall well-being and resilience in pigs raised under intensive production systems (Liao & Nyachoti, 2017).

Besides the auxinic application of probiotics, they find application therapeutically in pig farming to manage infective diseases and health challenges. For instance, probiotic supplements have been shown to reduce the severity and duration of diarrhea outbreaks associated with enterotoxigenic E. coli infections in piglets (Liao & Nyachoti, 2017). Additionally, probiotics help mitigate the impact of environmental stressors and optimize growth performance during critical phases such as

weaning, thereby supporting the overall health and productivity of pigs from nursery to finishing stages.

3.4. Administration of probiotics in companion animals

In companion animals, probiotics have shown promising effects in a variety of processes. Firstly, they enable managing gastrointestinal disorders, other than contributing to enhancing the overall immune response, which is particularly beneficial for older pets or those undergoing stressful situations like travel or changes in environment (Appanna & Appanna, 2018). Also, probiotics hinder infections in pets by supporting their immune system. Specifically, they stimulate immune responses in the gut-associated lymphoid tissue (GALT) and mucosal surfaces, where a significant portion of the immune system is located. Other mechanisms exploited for the probiotics include promoting a healthy gut microbiome, and directly inhibiting pathogenic bacteria. For instance, multiple species of Lactobacillus and Bifidobacterium help prevent and manage gastrointestinal infections in pets (Ellickson, 1985). They facilitate a balanced gut microbiota and excludes pathogenic bacteria as species of the genera Salmonella, Campylobacter, and Clostridium perfringens (Elbers et al., 2008; Ellickson, 1985). Along, probiotics strengthen and restore the intestinal barrier structure, reducing the risk of infections and improving digestive performances (Zinsstag, Schelling, Waltner-Toews, & Tanner, 2011). Administration of probiotics strains resulted in effective counteraction of the antibiotics side- effects. Thus, reducing the duration and severity of antibiotic-associated diarrhea and supporting overall recovery. Recent studies demonstrated that Lactobacilli, among others, can help maintain a healthy urinary tract environment by producing antimicrobial substances against uropathogens like E. coli (Song et al., 2022).

Stress can weaken pets' immune systems and increase their susceptibility to infections. Probiotics can help mitigate the effects of stress by producing neurotransmitters that regulate mood and stress responses (Madabushi, Khurana, Gupta, & Gupta, 2023).

In addition, probiotics applied orally or included in dental chews and treats can contribute to oral health in pets by reducing plaque formation, combating periodontal pathogens, and supporting gum health. This can help prevent oral infections and improve overall dental hygiene with important repercussions on the overall health status and animal wellness (Mäkinen, Mäyrä, & Munukka, 2019). Implementation of probiotics have also shown potential effects in managing dermatological conditions such as allergic skin diseases and infections caused by Malassezia yeast or Staphylococcus bacteria. Here, beneficial strains modulate the immune response by reducing inflammation, which may alleviate symptoms and support skin barrier function integrity (Bond et al., 2020).

3.5. Exotic animals

Probiotics administration in exotic animals can be applied to various species to support digestive health, immune function, and overall well-being. Unlike farm- and companion-animals, administration of probiotics to exotic animals has unique challenges and considerations, mainly linked to the animal management practices (Garcias-Bonet et al., 2024). Nevertheless, probiotics are, nowadays, administered to different types of exotic animals. In exotic avian species, probiotics administration demonstrated to support gastrointestinal health, especially during periods of stress or dietary changes. Alongside, other probiotic strains enhanced immune function in birds, helping to prevent infections and supporting animal health status. This is particularly beneficial in aviaries or breeding facilities where birds are more susceptible to stress-related illnesses (Smith, 2014).

Probiotics can aid in improving digestive function in reptiles, especially herbivorous species like tortoises and iguanas. They assist in breaking down plant fibers, enhancing nutrient absorption, and reducing the incidence of gastrointestinal issues such as constipation or impaction (Rawski, Kierończyk, Długosz, Świątkiewicz, & Józefiak, 2016). In addition, probiotics help treat microbial dysbiosis, a common condition for reptiles housed in captivity due to dietary changes or environmental stressors (Rawski et al., 2016). Similar effects have been observed in small mammals (e.g., Rabbits,

Guinea Pigs) where probiotics administration benefitted herbivorous small mammals by aiding them in the fermentation of dietary fiber in the cecum and colon. This enabled enhanced nutrient utilization, prevents gastrointestinal stasis, and reduces the risk of conditions like bloating.

Exotic mammals may experience stress during transportation, veterinary visits, or changes in the environment. Here, probiotics showed supporting these animals by modulating stress responses, and maintaining immune function.

Interestingly, probiotics can be used in aquaculture settings to improve water quality and support the health of fish. Beneficial bacteria can compete with and inhibit the growth of pathogenic organisms in the aquatic environment, reducing the incidence of infectious diseases and promoting fish health (Wang, Chuprom, Wang, & Fu, 2020). Also, oral administration of probiotics enhances nutrient absorption and utilization, particularly in omnivorous and herbivorous fish species. This improves growth rates, feed efficiency, and overall performance in aquaculture operations.

4. New frontiers of probiotic administration: tailored veterinary medicine

Probiotics administration in animals through a tailored veterinary medicine approach involves drawing probiotic therapy to the individual animal's specific health needs, microbiome composition, and response to treatment; among the other interfering environmental variables one might consider depending on the specific issue. Although highly variable, tailored approaches share some common steps. Before starting probiotic therapy, veterinarians may profile microbiome composition and assess diversity of the animal's gut microbiota. This identifies any dysbiosis that may be contributing to health issues to treat or prevent. Based on the microbiome analysis and the animal's health condition, veterinarians select probiotic strains that are most likely to benefit the animal (Singh & Natraj, 2021). This selection considers the specific benefits each strain is capable of, such as promoting co-occurrence of beneficial bacteria, production of antimicrobial substances, and/or enhancing immune function. This step is crucial as it is required to forecast the role of the novel strain(s) in the biotic and abiotic mileu where it is expected to be hosted. Also, it is pivotal to determine the optimal dosage and administration method for the probiotics chosen, based on the animal's species, age, weight, health status, and the severity of the condition being treated (Jugan, Rudinsky, Parker, & Gilor, 2017). Likely to pharmacological treatments, a follow-up of the animal's response to probiotic therapy is expected, evaluating parameters such as digestive health, immune function, and overall wellness status.

Probiotics may be integrated with other personalized veterinary treatments, such as dietary modifications, medications, and supplements. This holistic approach addresses multiple aspects of the animal's health and maximizes the effectiveness of treatment. Adjustments of the probiotic regimen are to be made possible according to the animal's individual response and/or any changes in health status either correlated or independent from the probiotic treatment. In this light, veterinarians should periodically re-assess the animal's microbiome and health status to adjust probiotic therapy, if needed, to sustain beneficial effects and prevent recurrence of health issues.

Overall, tailored veterinary medicine enhances the effectiveness of probiotics administration by customizing treatment plans to meet the unique needs of each animal. This approach ensures that probiotic therapy is targeted, evidence-based, and optimized for improving the animal's health and well-being. Collaborating with a veterinarian who is knowledgeable in probiotics and personalized medicine is essential for emphasizing the uniqueness of the animals' microbial community, modulating its finely tuned orchestration in favor of a long-lasting homeostatic balance without the administration of drugs or even the burdensome antibiotics.

In conclusion, probiotics represent a valuable tool for enhancing gut health, improving growth performance and supporting disease management in both companion animals and the animal production industry. By modulating the gut microbiota, boosting immune responses, and reducing the reliance on antibiotics, probiotics contribute to sustainable and efficient farming practices.

While probiotics offer numerous benefits, several challenges remain, including strain specificity, dosage optimization, and variability in efficacy across different production environments. Factors such as feed composition, management practices, and genetics can influence the effectiveness of probiotic supplementation. More research is needed to better understand the mechanisms of action of probiotics and to identify optimal formulations and application strategies for maximizing their health-promoting effects. As the understanding of probiotic interactions with the microbiome continues to advance, their integration into routine management practices holds great promise for promoting healthier and more resilient pig populations, worldwide.

5. Future Directions and Challenges

While the potential benefits of probiotics in animal health are substantial, several challenges remain. One critical consideration is the strain-specificity and dosage requirements for different animal species and health conditions. Moreover, the regulatory framework governing the use of probiotics in animal feed and healthcare products varies across regions, necessitating standardized guidelines for efficacy and safety assessments.

Future research directions include exploring novel probiotic strains, understanding their interactions with the host microbiota, and optimizing delivery methods to ensure viability and efficacy. Additionally, integrating probiotics with other nutritional strategies, such as prebiotics (which promote the growth of beneficial microbes) and synbiotics (a combination of probiotics and prebiotics), holds promise for synergistically enhancing animal health outcomes.

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