Probiotics, Prebiotics, Paraprobiotics, Postbiotics

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Abstract

Antibiotics have long been used to preserve animal health, improve growth, and increase efficiency in animal industries, but the overuse of antibiotics as growth promoters led to the development of resistant bacteria. As a result of this predicament, researchers investigated safer alternative biotechnological breakthroughs, which led notably to the use of probiotics (bacteria and yeast) and prebiotics as feed additives in livestock. Since then, the focus of research teams has shifted to more varied fields of application of probiotics and prebiotics, in animal nutrition. Nowadays, these additives are commonly included in feeds for various species of production animals (swine, poultry, ruminants, and aquaculture). Recently, paraprobiotics and postbiotics are also being studied. The reason for the inclusion of these "biotics" in animal feeds is wide: promotes animal health and productivity by enhancing gut health, nutrient utilization, as well as boosting immune system functionality and reducing foodborne pathogen carriage. In more recent years, an increased concern of the consumer on the sustainability of animal production has been recorded. This chapter aims at reviewing research findings on the potential application of "biotics" into an integrated approach of sustainable farming practices, which is not only limited in terms of environmental concerns but also about of combining profitability with an increase in animal welfare.

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1 Introduction

Since their discovery, antibiotics have been used to increase growth in a variety of animal species by adding them to their meals, to cure infectious diseases, or prevent them when given in sub-therapeutic levels. However, besides killing the vulnerable bacteria, the administration of antibiotics results in the development of some resistant strains. These resistant strains grow in number over time and may spread resistant genes to other bacteria. These resistant bacteria may spread from one host to another, either directly or indirectly, reduce the potency of medications, and lead to antibiotic resistance (Palma et al. 2020). Such gene transfer can occur horizontally between bacteria or vertically during reproduction of the bacteria, from one ecosystem to another (animal to human, environment to human but also human to animal, e.g., (Beukers et al. 2018) in intensively reared cattle, (Hedman et al. 2020) in poultry farming systems with the risk of sharing at once the multiple resistance genes hosted by one microorganism to another bacterial species (Sun et al. 2019; Lerminiaux and Cameron 2019). As a result, a global movement to reduce the use of antibiotics in animals has been applied, and many countries have outlawed their usage (Castanon 2007; FDA 2012).

Several microbes have developed resistance as a result of improper antibiotic treatment: *Pseudomonas aeruginosa* has developed resistance to carbapenems, quinolones, aminoglycosides, cephalosporins, penicillins, and monobactam (Odoi 2016); Resistance to β-lactams has evolved in *Staphylococcus* species (Mamza et al. 2010); Ampicillin, tetracycline, trimethoprim, ciprofloxacin, and sulfamethoxazole are no longer effective against *Salmonella* spp. and *Escherichia coli* (Medeiros et al. 2011; Van den Bogaard and Stobberingh 2000). More bacteria have already emerged or may do so in the near future if the current epidemic of antibiotic resistance does not end.

In order to prevent the reduction in animal production performance and financial losses, alternatives are more in demand as a result of the limited use or ban of antibiotics in feed. Since the late 1990s up until the present, nutritionists and pharmacists have been working on producing various replacements to preserve or enhance animal health and performance. The use of probiotics and prebiotics, which have demonstrated their effectiveness for both humans and animals, is one alternative with high expectations. Additionally, during the past 10 years, studies on paraprobiotics and postbiotics have produced encouraging results that justify their use.

In terms of definition, probiotics are living bacteria that benefit their host when given in sufficient quantities (Arora and Baldi 2015). Regarding prebiotics, the sixth Meeting of the International Scientific Association of Probiotics and Prebiotics (ISAPP) defined them as “a selectively fermented ingredient that results in specific changes in the composition and/or activity of the gastrointestinal microbiota, thus conferring benefit(s) upon host health" (Gibson et al. 2010). Paraprobiotics are characterized as non-viable, inactivated microbial cells that provide the host with health benefits (Siciliano et al. 2021). Last but not least, postbiotics are the complex mixture of metabolic products secreted by probiotics in cell-free supernatants such as enzymes, secreted proteins, short chain fatty acids, vitamins, secreted biosurfactants, amino acids, peptides, organic acids, etc. (Nataraj et al. 2020).

Probiotics and prebiotics have the potential to reduce the environmental impact of meat, milk, egg, and fish production. By improving feed efficiency, probiotics can contribute to a better utilization of the feed, hereby reducing the carbon footprint per unit of food produced. Their potential effect on digestibility allows the farmers to have more flexibility on the feed stuffs they provide to the animals. This can also allow for more locally grown raw materials to be included in feed rations. In addition, better utilization of the feed by the animal should result in lower losses on N and P into the environment via the animal excretions. The positive effects probiotics and prebiotics can have on animals' immunity and disease resistance, can contribute to an improved animal welfare. In addition to probiotics, postbiotics have also been gaining attention as a potential solution for improving animal health and productivity. Postbiotics refer to the metabolic by-products of probiotics, such as organic acids and peptides, that have been shown to have health-promoting effects. Unlike probiotics, which are live microorganisms, postbiotics are non-viable and therefore do not carry the risk of pathogen contamination. The use of postbiotics in animal nutrition has the potential to have all the benefits of probiotics without their side-effects, making it a promising area of research. However, the research is still in its early stages, and there are many new things to learn for all the type of "biotics" and their potential applications. This review will attempt to explain all the recent advances in the field of probiotics, prebiotics, paraprobiotics, and postbiotics, along with what the most recent research has revealed about how they function in various organs and how they improve animal health.

2 Probiotics

History The phrase "probiotic" is contrasted to the term "antibiotic" and is derived from the Greek words "pro" and "bios," that together mean "for life." Elie Metchnikoff, a researcher at the Pasteur Institute in Paris, was the pioneer in the field of probiotics. In 1907, as he was working in Bulgaria, he discovered that Bulgarian peasants who consumed a lot of spoiled milk lived longer than average. This confirmed Metchnikoff's hypothesis that bacteria from the sour milk would have an impact on the lower gut and general health. From there, Metchinkoff made the decision to continue his research and his findings encouraged other researchers from around the world to start their own research on probiotics. Later in 1965 Probiotics were redefined by Lilley and Stillwell. They defined probiotics as microbes that would promote the growth of other beneficial microbes in the intestines (Lilly and Stillwell 1965). Probiotics were more clearly described by

Fuller in 1992 as "a live microbial feed additive that benefits the host animal by enhancing its gut microbial balance" (McFarland 2015). Since the discovery of *Lactobacillus acidophilus* in 1890 and Henry Tissier's discovery of the species of *Bifidobacteria* later that same decade, scientists have been able to isolate numerous strains of good bacteria for the digestive tract. After that, Henri Boulard discovered the probiotic yeast *Saccharomyces boulardii* in 1923 and Minoru Shirota identified a novel strain of *Lactobacillus casei* in the 1930s. Since then, other helpful bacteria have been discovered, and there will undoubtedly be many more in the future.

The most frequently used probiotics in animal feed are the genera *Bifidobacterium* (*thermophilum, pseudolongum, longum*) (Mattarelli and Biavati 2018), *Bacillus* (*subtilis*) (Cutting 2011), *Lactobacillus* (*acidophilus*, *bulgaricus*, *plantarum*), *Lactococcus* (*lactis*), *Enterococcus* (*faecalis*, *faecium*), and *Saccharomyces* (*cerevisiae*, *boulardii*) (Muzaffar et al. 2021). Probiotics can be given in feed or water as a single strain, a multi-strain mixture, or as an addition to other feed additives. It is generally agreed upon that probiotics containing multiple strains are more beneficial than those containing a single strain due to their synergistic effects (Bhogoju and Nahashon 2022).

For their use to be optimized, probiotics must first be evaluated for their safety, and this is a challenging process. Probiotic organisms that adhere to the digestive tract must endure harsh conditions and must have a positive impact on the stability and security of the intestinal environment. Additionally, they should affect the way digestion, metabolism, and the immune system respond (Patel et al. 2015). The selection of novel probiotic organisms entails choosing the strains and even genera of microbes that have the most advantageous or targeted effects. The evaluation mainly focuses on security and the benefit-to-risk ratio connected with the use of a specific probiotic strain. Furthermore, probiotic strains added to feed should be resistant to pelleting temperatures and pressures, humidity, and the effects of harmful compounds during feed handling and storage, such as heavy metals or mycotoxins. The probiotics' peak duration of activity in feed and premixes cannot be less than 4 months. Encapsulating formulas allows for a longer survival time for strains, extending that time frame (Hollister et al. 1989) (Fig. 1).

Mechanism of Action The mechanisms of action of probiotics are still not entirely understood because they are numerous, diversified, and strain-specific. Some known mechanisms include pathogen exclusion and bacteriocin production, modulation of fecal enzymatic activities, production of short-chain and branched-chain fatty acids, cell adhesion and mucin production, immune system modulation, and interaction with the brain-gut axis via regulation of endocrine and neurologic functions.

Competitive exclusion occurs when one species of bacteria outcompetes other species for receptor sites in the intestinal tract (Bermudez-Brito et al. 2012). These events can occur as a result of a decrease in the pH of the surrounding environment, competition for nutritional sources, and the production of bacteriocin or bacteriocin-like substances (Collado et al. 2010). Moreover, probiotics can change the metabolism of bile acids in the gut lumen, which in turn affects how much cholesterol is absorbed. Most known probiotics and bacterial species from numerous genera

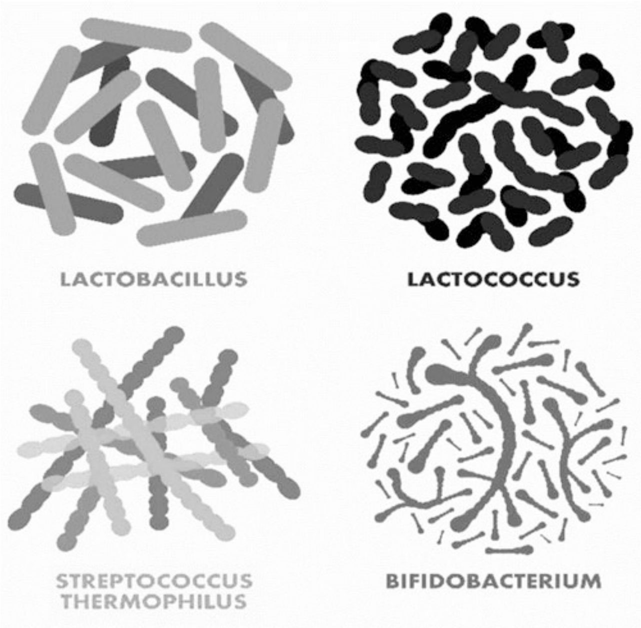
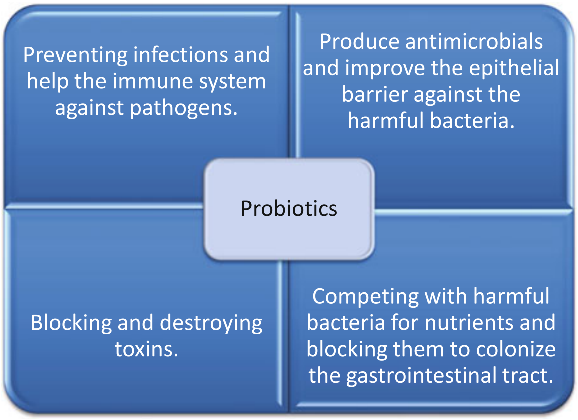


Fig. 1 Shape of different probiotic bacteria

associated with the digestive tract generate bile salt hydrolase, an enzyme that may take part in the initial reaction of the deconjugation of biliary salts (Pavlovic et al. 2012). The immune system is modulated by the gut microbiota through the synthesis of chemicals that have anti-inflammatory and immunomodulatory properties and can activate immune cells. Probiotic bacteria interact with epithelial cells and DCs, as well as macrophages and lymphocytes, to provide these immunomodulatory effects (D'Amelio and Sassi 2017). The imbalance of the gut microbiota can influence the brain-gut axis and may be directly related to stress brought on by either physical or environmental reasons (Dinan et al. 2006). Overall, the neurological, endocrine, and immunologic mechanisms underlying the impacts of the gut intestinal microbiota on the central nervous system are complex, although these effects are thought to primarily occur via the creation of bacterial metabolites (Ong et al. 2018). Gut bacteria produce a wide range of neuroactive substances, including dopamine, γ-aminobutyric acid, histamine, acetylcholine, and tryptophan, which is a precursor in the production of serotonin (Fig. 2).

Probiotics on Performance Although more research is needed to determine the exact mechanism by which probiotics improve growth performance, research findings have shown that they are growth promoters, they decrease the impact of stress and mitigate the severity of disease by altering the gut environment and enhancing gut barrier function through the strengthening of useful gut microflora, competitive exclusion of pathogens, and immune system stimulation.

Fig. 2 Mechanism of action



Lactobacillus has demonstrated to be quite powerful in broiler development performance, according to numerous studies (Gao et al. 2017). When *Lactobacillus* was added to the diet of layer chickens, the egg weight increased (Pambuka et al. 2014). The same results were observed in terms of growth, performance, and survival rate when fish were supplemented with *Lactobacillus* (Selvaraj and Bogar 2019; Rahman et al. 2019). In ruminants, *Lactobacillus* is used in young calves, where it has been observed to improve weight gain (Al-Saiady 2010). *Lactobacillus* increased the rate of weight gain in pigs weaned at 21 days because the synthesis of digestive enzymes improved meal conversion (Tian et al. 2020). A substantial portion of the animal microbiota is made up of the genus *Lactobacillus*, which is composed of Gram-positive, anaerobe, non-spore producing bacteria. There are 44 species of *Lactobacillus* presently (Zheng et al. 2020).

Bifidobacterium greatly boosts production effectiveness, feed conversion, and weight gain in poultry (Palamidi et al. 2016). Similar outcomes *Bifidobacterium* generates in the fish affecting the overall health and the growth performance (Khalafalla et al. 2020). The genus *Bifidobacterium* is a Gram-positive, non-motile, and frequently branched anaerobic bacteria. One of the most important bacterial genera that contributes to the microbiota of the gastrointestinal tract in mammals is the *Bifidobacteria*.

Another probiotic strain that has been used as a growth promoter is *Bacillus* sp. which have been shown to improve broiler overall body weight gain (Wang et al. 2016a). Moreover, *Bacillus* has been shown to boost egg production, egg production, eggshell calcium content, thickness, and weight in laying hens (Wang et al. 2021; Li et al. 2006). A more recent study found that *Bacillus pumilus* increased final weight and weight gain, and improved feed conversion ratio when administered in broilers. It also increased counts of *Lactobacillus* and *Bacillus* spp. in the ileum and the ceca (Bonos et al. 2021). In fish, *Bacillus* improved the growth rate, survival, and weight gain (Sadat Hoseini Madani et al. 2018) and when administered in rainbow trout improved the growth rate and the feed efficiency (Giannenas et al. 2014). In Holstein calves the intake of dry matter and average daily gain were both enhanced by *Bacillus* (Zhang et al. 2016). Finally, in swine production inclusion of *Bacillus* complex to the diet increased daily average gains and feed consumption (Ahmed et al. 2014). Additionally, Cai et al. (2015) found that adding dietary probiotics based on the *Bacillus* strain enhanced average daily gain during days 0–14 following weaning and had a beneficial impact on raising gain/feed ratios between days 0 and 42.

Lastly, *Saccharomyces cerevisiae*, a probiotic yeast that is frequently employed, has been demonstrated in studies to dramatically boost the body weight gain of broilers feed consumption and feed conversion efficiency (Shareef and Al-Dabbagh 2009). Additionally, a study revealed that layers treated with *Saccharomyces cerevisiae* produced noticeably more eggs (Hassanein and Soliman 2010). The same outcomes were observed in terms of improved feed consumption and growth performance when *Saccharomyces* were administered to fish (Jahan et al. 2021). Moreover, supplementing horses with yeast can enhance dietary digestion and assimilation of food nutrients which results in better equine performance (Julliand et al. 2006). *Saccharomyces cerevisiae* has been also shown to enhance performance in dairy ruminants, with the most recurrent benefits being an increase in dry matter intake and milk output (Poppy et al. 2012). Furthermore, it has been demonstrated that probiotic yeast increases some beef cattle productivity indicators which includes the ability to digest their food and improved growth performance (Batista et al. 2022). In swine industry supplementing sows with *S. cerevisiae* increased the number of piglets born and the percentage of live births. Another study found no difference in growth performance between pigs fed diets supplemented with yeast and pigs fed antibiotic growth boosters (Agazzi et al. 2015; Shen et al. 2009).

Probiotics on Immune Response An organism must be healthy and have a strong immune system in order to thrive and prosper. Because of this, antibiotics have been used for a long time to encourage growth or act as a prophylactic against potentially hazardous microorganisms. However, due to excessive antibiotic use, the emergence of novel pathogens that are resistant to antibiotics is something that veterinarians frequently discover in livestock. For this reason, probiotics are currently regarded as the best antibiotic alternative that secures health and encourages growth.

It has been demonstrated that *Lactobacillus* affected the chemokine gene expression and cytokine production in the intestinal epithelium of broiler chickens. A further way that *Lactobacillus* affects the immune system is through boosting β-lymphocytes production of antibodies, increased the blood CD4+ lymphocyte count as well as interferon and tumor necrosis factor expression in the ileum (Haghighi et al. 2008). According to another study, vaccination and *Lactobacillus* together with probiotic mix may have worked synergistically to reduce the amount of *Salmonella enteritidis* in broilers (Praharaj et al. 2015). The same outcomes against salmonella were reported in laying hens following vaccination and *Lactobacillus* supplementation (Groves et al. 2021). Except *Salmonella*, *Lactobacillus* has shown good results against *Eimeria* sp. by lowering the quantity of oocysts in the feces and raising the levels of CD3, CD4, and CD8 lymphocytes as well as IL-2 interleukin in the intestines of poultry with *Eimeria acervulina* infection (Dalloul et al. 2003). The same results against *Eimeria* were reported by Giannenas et al. (2012) who administered a combination of *Lactobacillus*, *Bacillus*, and *Bifidobacterium* in broiler chickens challenged with *Eimeria* spp. In fish, *Lactobacillus* boosted lysozyme and IgM, enhanced immunological responses, and increased disease resistance (Hassani et al. 2020). Additionally, *Lactobacillus* spp. led to a significant improvement in immune responses as well as a reduction in the overall mortality rate after challenged with *Vibrio harveyi* infection (Geng et al. 2012]). A similar type of animal response on reduced mortality was reported by Castex et al. (2008, 2010) in Vibrio challenged shrimps supplemented with a strain of *Pediococcus acidilactici*.

In horses, *Lactobacillus* in combination with *Enterococcus* lowered the frequency of diarrhea in newborn foals and reduced the incidence of *Salmonella* shedding by about 65% in probiotic-treated horses (Ward et al. 2004). Furthermore, in another study, strains of *Lactobacillus* reduced pathological score in inflammatory bowel disease, increased colon length, and controlled the cytokine release (Qin et al. 2022). In ruminants, the administration of a mixture consisting of various *Lactobacillus* species to dairy calves resulted in an improvement of the animals' overall health. The mortality and morbidity rates tended to be lower (Maldonado et al. 2017). In young calves, *Lactobacillus* bacteria are most frequently employed because they lower the number of Gram-positive bacteria present. Early *Lactobacillus* administration to calves is particularly advantageous as it enhances immunocompetence, lowers the occurrence of diarrhea cases by more than 70%, and speeds up T-cell transformation (Zhang et al. 2016; Al-Saiady 2010). *Lactobacillus* raises insulin and blood sugar levels in dairy cows and stimulates macrophages to generate cytokines (Matsuguchi et al. 2003; Oetzel et al. 2007). In pregnant cows, *Lactobacillus* reduced the incidence of metritis, uterine infections, and laminitis (Deng et al. 2015). Finally, *Lactobacillus* altered the gut microbiota of goats by decreasing *Salmonella/Shigella*-like enterobacteria and by increasing other lactic bacteria (Apas et al. 2010).

Supplementing neonatal pigs with *Lactobacilli* aids in the early establishment of a stable gut flora, boosts the immune system, and stops diarrhea. In neonatal pigs, oral treatment of *Lactobacillus* enhanced intestinal health, increased *Lactobacilli* and *Bifidobacterium*, and decreased the number of possible entero-pathogens such as *E. coli* and *Clostridia* (Liu et al. 2014; Chiang et al. 2015). Similar outcomes were observed earlier when *Lactobacillus* was administered to piglets that had been exposed to *E. coli*; *Lactobacillus* improved T-cell differentiation and triggered cytokine production in the ileum (Wang et al. 2009). *Lactobacillus* exhibited similar advantages when administered to grower-finisher pigs (Giang et al. 2011). In companion animals, *Lactobacillus* administration to puppies prevented gastrointestinal infection (Fernández et al. 2019). When administered to dogs with gastrointestinal disorders, lactic acid bacteria populations increased, clostridia populations declined, and some Gram-negative bacterial genera were also reduced. Blood samples also showed improvement in total protein, cholesterol, and ALT levels (Strompfová et al. 2017). Similar results were shown in cats, where *Lactobacillus* increased the beneficial bacteria and decreased the harmful bacteria *Clostridium* spp.

and *Enterococcus faecalis*. Additionally, it reduced plasma endotoxin levels, causing systemic and immunomodulatory modifications in the treated cats (Marshall-Jones et al. 2006).

Despite not being as popular as *Lactobacillus*, using *Lactococcus* has demonstrated some positive effects on the regulation of the immune system. In broilers, *Lactococcus* and inulin administration affected the development of central and peripheral lymphatic organs and improved immune responses related to stimulation of Peyer's patch and cecal tonsil colonization by T-cells (Madej et al. 2015). The administration of *Lactococcus* in fish increased lysosomal activities and production of IL-12 and IFN-g. Additionally, it demonstrated potent antibacterial properties against the dangerous pathogens *Streptococcus* and *Enterococcus*. Only 5.7% of the control group survived at 20 days after being challenged with *Streptococcus iniae*, compared to 65.7% of those who consumed *Lactococcus*, demonstrating a considerable level of protection (Kim et al. 2013). Similar findings were made in a different study that suggested *Lactococcus* regulated innate immune parameters and provided protection against *Streptococcosis* (Hasan et al. 2018). According to results of another study, *Lactococcus* can be employed as a vaccine carrier that may provide protection against multiple Vibrio species and can enhance T-cell numbers, cytokine production, and innate immune responses (Lee et al. 2021). In ruminants, *Lactococcus* effects have been studied extensively as a therapy for mastitis in dairy cows. All studies have concluded that it is a promising candidate strain for either mastitis prevention or therapy (Bouchard et al. 2015; Malvisi et al. 2016). In swine, *Lactococcus* is frequently administered to weaning piglets to lessen the likelihood of diarrhea and to regulate intestinal immunity. According to a study, *Lactococcus* increased the expression of the genes for the anti-inflammatory cytokines while suppressing the expression of interleukin-g in the jejunum and interleukin-22 in the ileum (Yu et al. 2021).

Bifidobacterium is another useful probiotic for the immune system. *Bifidobacterium*, in particular, it has typically been viewed as an anti-inflammatory, it has been shown to interact with immune cells, and modify immunological pathways. *Bifidobacterium* treatment improved IFN levels in chickens with *Clostridium* infections, had an anti-*Campylobacter* effect, and increased the production of antibodies against the Newcastle disease virus in layers (Kim et al. 2007; Santini et al. 2010; Hatab et al. 2016). Additionally, in broilers, *Bifidobacterium* and lactic acid bacteria increased systemic immunity and local antibody production (Haghighi et al. 2006). Finally, it has been shown that *Bifidobacterium* probiotic strains raised the levels of immunoglobulin (Ig) A, G, and M in broilers and turkeys, which improves the disease resistance (Abdel-Moneim et al. 2019). The same outcomes were observed in fish, where *Bifidobacteria* were used to stimulate the creation of immunostimulants in the fish intestines that prevented the growth of several pathogenic bacteria (Mussatto and Mancilha 2007). These conclusions are supported by two further studies, where *Bifidobacterium* use led to an enhanced overall fish health (Hassani et al. 2020; Khalafalla et al. 2020).

In ruminants, *Bifidobacterium* usage is more prevalent in young calves. Young calves given *Bifidobacterium* and *Lactobacillus* throughout the early stages of life gained more weight and experienced fewer diarrheal episodes. Likewise, giving probiotic *Bifidobacteria* to calves reduced the levels of *E. coli* and total coliforms while raising the relative abundance of *Lactobacilli* (Shehta et al. 2019; Geigerova et al. 2016). Another study found that the administration of *Bifidobacterium* was able to raise interferon (IFN) levels. This could have a major impact on intestinal viral defense because of IFN's ability to boost the expression of antiviral proteins that can reduce or inhibit viral replication (Kobayashi et al. 2017). In weaned pigs, *Bifidobacterium* improved gut health and immunity, and decreased the pathogen number after the *Salmonella* challenge (Herfel et al. 2013; Barba-Vidal et al. 2017). Similar to this, a recent study discovered that taking *Bifidobacterium* orally can prevent *Salmonella* infection (Splichalova et al. 2021). Additionally, another study suggests that *Bifidobacterium* modifies gut microbiota, enhances intestinal barrier function, and regulates inflammatory cytokines (Arenas-Padilla et al. 2018). Finally, a microbiota analysis revealed that a diet supplemented with *Bifidobacterium animalis* significantly increased the relative abundances of beneficial bacteria. This study also demonstrated that using *Bifidobacterium* significantly improved growth performance and reduced diarrhea incidence (Pang et al. 2022).

Another probiotic that stimulates immunity is *Bacillus*. Their capacity to naturally generate spores that resume viability under favorable conditions gives them a significant edge over other probiotic species. *Bacillus* species frequently have the ability to activate the host immune system in chickens. According to research by (Mingmongkolchai and Panbangred 2018), *B. subtilis* may be involved in the enhancement of the IgA response, which is essential for protection against mucosal infections. In addition, Lee et al. (2015b) displayed immunological responses to *Eimera* spp. and *Clostridium perfringens*, the causal agents of necrotic enteritis. Khaksefidi and Ghoorchi (2006) showed that feeding *B. subtilis* to broiler chicks had a favorable effect on antibody generation against Newcastle disease. By boosting the number of intraepithelial lymphocytes and immunoglobulin-producing cells, *Bacillus* spores are said to aid in the development of the gut-associated lymphoid tissues (Molnár et al. 2011). According to a study by (Wang et al. 2018b), *B. subtilis* was able to reduce inflammation brought on by heat stress by producing more anti-inflammatory cytokines.

The use of *Bacillus* in aquaculture resulted in an improvement in immunological function overall, a rise in survival rates, and an increase in phagocytic, respiratory burst, catalase, nitric oxide synthase, acid phosphatase, amylase, and protease activities (Zhao et al. 2019). According to another report, adding *Bacillus subtilis* as a probiotic to a diet improved fertility, viability, and the quantity of normal fry generated (Ghosh et al. 2007). Finally, but certainly not least, the use of bacillus in fish has shown that it can reduce Vibrio populations and defend against *Aeromonas hydrophila* (Hostins et al. 2017; Devi et al. 2019). In horses, despite not being able to colonize the equine intestinal system, *Bacillus* organisms can survive in the large intestines of horses for up to two days and may even have positive effects by preventing the proliferation of harmful bacteria. Therefore, bacillus research on this species is not as frequent. According to research, bacillus has been effective against *Clostridium* spp., *E. coli*, *Salmonella* spp., *Rhodococcus equi*, and

Streptococcus equi. Moreover, horses are susceptible to developing intestinal bacterial overgrowth, enterocolitis, and diarrhea. Considering this, researchers looked into how *Bacillus subtilis* affects pathogenic elements in the equine digestive tract that frequently thrive despite antibiotic treatment (Burke and Morre 2017).

In ruminants, bacillus has been utilized in dairy cows where it enhanced milk IgA and lowered serum haptoglobin (Luan et al. 2015). According to a recent study, a combination of *Lactobacillus plantarum* and *Bacillus subtilis* used in Holstein calves as dietary supplements has been shown to have positive effects on the immune system because they boost the rate of T-cell transformation and decrease cortisol levels (Zhang et al. 2016). Last but not least, a study that was done to manage mastitis problem in dairy cows revealed that bacillus genera can limit the growth of mastitis pathogens more effectively against Gram-positive *S. aureus*, *S. epidermidis*, or *Trueperella pyogenes* than against Gram-negative *E. coli* or *Klebsiella* (Woodward et al. 1987). The use of *Bacillus* in swine revealed that piglets exposed to *Escherichia coli* had considerably higher serum IgG levels (Ahmed et al. 2014). Another study discovered that the use of a *Bacillus subtilis* mixture in sows before and throughout lactation could increase the number of piglets born overall and born alive, improve beneficial bacteria counts, and reduce the concentration of dangerous bacteria in the piglets' small intestine after birth (Baker et al. 2013). (Link et al. 2016) found that adding *Bacillus* to a breastfeeding piglet's diet decreased the diarrhea score.

Enterococci are common in the environment as commensal and pathogenic microorganisms, as well as gut symbiotic organisms. The *Enterococcus* spp. strains are well adapted to various food systems because of their tolerance to salts and acids. Additionally, a variety of *Enterococcus* strains have been found to produce bacteriocins and other antimicrobial substances. *Enterococcus* is a genus that has not yet been given the classification of "generally recognized as safe," although some of its species are employed as probiotics and feed additives to stop diarrhea or boost animal development (Franz et al. 2011). In chicken, Enterococcus was employed, and the outcome was an increase in IgA production (Beirão et al. 2018). In all other studies, *Enterococcus* was combined with various beneficial bacteria, and the results included a notable increase in the weight of immunological organs and antibody production, an improvement in antibody levels against the virus that causes Newcastle disease, and the induction of an anti-inflammatory response (Kabir et al. 2004; Hatab et al. 2016; Palamidi et al. 2016). A combination of *Enterococcus* and *Lactobacillus* strains had good effects in vitro, according to (Chaveerach et al. 2004), but only native bacteria obtained from adult chickens could protect young broilers from *Campylobacter* colonization. A more recent study found that the use of *Enterococcus faecium* can improve intestinal barrier damage caused by necrotic enteritis (Wu et al. 2019). Comparable results were observed in fish once *Enterococcus* was applied to their meal. All the studies found enhanced immunity and an increased survival rate. Particularly, Chang and Liu (2002) found that the administration of *Enterococcus* enhanced disease resistance against *Edwardsiella tarda* a well-known cause of hemorrhagic septicemia in fish. Later Wang et al. (2008) concluded that the use of *Enterococcus* influenced the immune system by increasing blood phagocyte respiratory burst activity. Lastly, Talpur et al. (2014) found that *Enterococcus* can enhance immunity and defense against infection by *Aeromonas hydrophila*.

In horses, *Enterococcus* is used in combination with other probiotics or prebiotics. Results from research by (Ward et al. 2004) on the decrease of *Salmonella* fecal shedding were encouraging. An oral gel product comprising *Lactobacillus* and *Enterococcus faecium* was given to the horses during the trial. The incidence of *Salmonella* shedding decreased as a consequence. On another study the use of *Enterococcus* in combination with Fructooligosaccharides triglyceride and cholesterol levels dropped, HDL and LDL concentrations in the treated horses were highest and lowest, respectively, and IgM levels were higher (Saeidi et al. 2021). In ruminants, the usage of *Enterococcus* is not so common. In a 2014 study conducted on dairy cows, it was shown that using *Enterococcus* and *Saccharomyces* together reduced the illness incidence of retained placenta, milk fever, metritis, endometritis, mastitis, ketosis, lameness, and other conditions (AlZahal et al. 2014). In several studies on pigs, it was discovered that adding *Enterococcus faecium* to the diet or feeding piglets a diet containing both *E. faecium* and other *Lactobacillus* strains greatly reduced postweaning diarrhea (Büsing and Zeyner 2015; Szabo et al. 2009; Vrotniakienė and Jatkauskas 2013). *Enterococcus faecium* treatment also shortens and decreases rotavirus shedding in pigs (Kreuzer et al. 2012). Other studies in pigs treated with *E. faecium* and challenged with *Salmonella typhimurium* DT104 showed that, despite the treated pigs' earlier and more intense development of humoral immunity, the excretion of *Salmonella* in feces and the colonization of organs increase without the presence of severe clinical signs of salmonellosis (Simon 2010; Szabo et al. 2009).

According to research on the yeast *Saccharomyces*, adding it to a diet can raise feed effectiveness, improve feed digestibility, boost animal performance, lower the quantity of harmful microorganisms, improve animal health, and lessen the negative environmental effects of farming animals. According to Bai et al. (2013), *Saccharomyces cerevisiae* and *Lactobacillus* probiotics increased the mRNA expression of TLR-2 and TLR-4 in the chicken's foregut. On another study made by Ajiguna et al. (2021) *Salmonella*-challenged broilers who received *Saccharomyces cerevisiae* as a dietary supplement gained weight and maintained their immune response. The same outcome found (Gingerich et al. 2021) where *Saccharomyces* reduced ***Salmonella enteritidis*** concentrations in the ceca. According to Paryad and Mahmoudi (2008), broiler chicks' blood cholesterol and heterophils/lymphocytes ratio both significantly decreased when *Saccharomyces cerevisiae* was introduced to their diet. Smialek et al. (2018) showed that a multispecies probiotic containing a mixture of Lactic Acid Bacteria and *Saccharomyces cerevisiae*, given to *Campylobacter*-challenged birds with as a supplement in their feed for the duration of the production cycle, was capable of lowering the *Campylobacter* population count in broiler ceca and feces. In this instance, the experimental birds' *Campylobacter* spp. count was around ten times lower than that of the control chickens.

Administration of *Saccharomyces cerevisiae* to fish enhanced development, improved immunological and antioxidant function, and improved disease resistance

(Abdel-Tawwab et al. 2008; El-Nobi et al. 2021). Another study found that administering *Saccharomyces cerevisiae* and *Bacillus* spp. reduced plasma cortisol levels, indicating improved stress tolerance and consequently better immunological function (Sutthi and van Doan 2020). Last but not least, a study on *Saccharomyces cerevisiae* found that some strains had potential as probiotics and aflatoxin B1 adsorbents when utilized in simulated fish digestive system settings (Pinheiro et al. 2020). In a study on the immunological response in horses, *Pediococcus* and *Saccharomyces boulardii* were mixed to examine their combined product. The study's findings demonstrated that the probiotic utilized raised neutrophil and immunoglobulin G concentrations. The outcomes showed that the probiotic administered had a positive impact on the system's immunity (Furr 2014). Another investigation on the administration of *Saccharomyces boulardii* in horses with acute enterocolitis revealed a substantial reduction in the severity of diarrheal sickness (Desrochers et al. 2005).

In ruminants, the administration of *Saccharomyces* to veal calves decreased occurrences of diarrhea and preserved a robust microbiota with Fecalibacterium as a dominant strain (Villot et al. 2019). In a different trial on calf rearing, providing calves with a synbiotic combination containing saccharomyces and prebiotics increased average daily growth and decreased the amount of *Escherichia coli* in the feces (Roodposhti and Dabiri 2012). Finally, Spaniol et al. (2014) discovered increased blood levels of TNF-α, IL-4, INF-γ, and serum globulins in dairy cows. A probiotic yeast applied to piglets has been shown in the majority of studies to have positive health effects. *Saccharomyces cerevisiae* may enhance mucosal immunity by increasing IgM and IgA activities against pathogens, promote intestinal development and function, adsorb mycotoxins, modulate gut microbiota, and lessen post-weaning diarrhea (Kogan and Kocher 2007; Shen et al. 2009; Jiang et al. 2015). Additionally, a live yeast supplement may boost the proliferation of gut cells in the mucus of pigs that have received it, enhancing their resistance to pathogenic invasion (Bontempo et al. 2006). Because the beta-D-glucans in yeast cell walls boost the activity of neutrophils and macrophages by attaching to their receptors and triggering cytokines, as well as raising the generation of antibodies, many positive benefits of yeast are proposed to stimulate immune-modulation (Kogan and Kocher 2007; Kim et al. 2017).

Probiotics on Intestinal Morphology and Digestibility Gut health and microbiota have a direct impact on an animal's ability to develop and function. In addition to becoming more effective at absorbing nutrients, a healthy gut is better resistant against harmful microbes. The animals benefit from a healthy microflora in a variety of ways, including by preventing the invasion of infections through bacterial competition or by occupying the attachment site in the gut and obstructing bacterial activity. Although the gut microflora is rather stable, several external conditions and an animal's state of health can affect it. Diet is the main element that influences the gut microbiota. Typically, probiotics are used to control the gut flora. Animal health and performance also depend on gut morphological factors since increased absorption area and nutrient absorption are strongly correlated with greater villus length to crypt depth ratios and higher villus height. Another indicator of better digestion is the number of goblet cells in the intestinal villi, since these cells decrease the likelihood of harmful bacteria adhering to the intestinal epithelium and increase mucin synthesis. Probiotics improve gut histomorphology.

Gao et al. (2017) fed *Lactobacillus plantarum* strain to broilers and found increased the proliferation of several intestinal *Lactobacillus* species and sped up the maturation of the intestinal microbiota. Earlier, similar findings were made by Lan et al. (2003), who discovered that *Lactobacillus* species maintained the natural balance of gut microorganisms and boosted the population of beneficial microflora. Palamidi et al. (2016) used *Lactobacillus* strains to examine the effect on digestibility and found significant improvement in the apparent total tract digestibility of lipids, crude protein, and ileal dry matter. In fish, *Lactobacillus* usage promoted intestinal microvilli length and growth (Pirarat et al. 2006). In another study, feeding fish exposed to cadmium with *Lactobacillus* reversed the alterations in their intestinal microbiota's composition and decreased the amount of flavobacterium and pseudomonas (Zhai et al. 2017). In two more investigations, *L. plantarum* significantly increased food intake, food absorption, and food conversion (Seenivasan et al. 2014; Sivagami and Ronald 2016). According to Suo et al. (2012), *Lactobacillus* caused an increase in the villus height of the ileum, jejunum, and duodenum in pigs. Another study on weaned pigs found that the villus height of the ileum was increased, the crypt depth in the duodenum was decreased, and the villus height to crypt depth ratio of the jejunum and ileum was also improved (Yi et al. 2018). Later, a different research came to the conclusion that the jejunum and ileum had a considerably higher ratio of the villus height to the crypt depth following *L. plantarum* treatment. The *L. plantarum* administration raised the mRNA abundance of pBD2 and pBD3 in the jejunum and ileum. The colonic microbiota's structure was also considerably altered by the *L. plantarum* therapy, with an increase in the phyla *Firmicutes*, *Actinobacteria*, and *Lactobacillus* (Wang et al. 2019b).

Bacillus species have same results as *Lactobacillus* on the intestinal morphology and digestibility. Hayashi et al. (2018) gave *B. subtilis* to broilers and discovered that better histologic modification was linked to the development of the defensive response in the ileum. Broilers' intestinal histology and microbiota are considerably improved by supplementing with *B. subtilis* alone or in conjunction with *S. boulardii*. Intestinal villus height, length, and goblet cell count all showed substantial improvements, with reduced crypt depth and much lower numbers of *Salmonella*, coliforms, and *E. coli* in the cecum (Rajput et al. 2013; Manafi et al. 2017). According to research made by Haque et al. (2021), the treatment of two strains of *Bacillus* resulted in a significantly greater amount of gut microbiota. According to histological data, probiotic administration throughout the nursing stages resulted in a favorable alteration in the gut morphological structures. Another study found that after 6 weeks of feeding, *B. cereus* and *B. subtilis* significantly improved the autochthonous gut microflora populations and stimulated a wide range of potential probiotics (Xia et al. 2020). *Bacillus* was administered to pigs, and Cai et al. (2015) found that this lengthened the villi of the duodenum and jejunum. In the ileum, Deng et al. (2020) discovered a rise in villus height and the villus height:crypt depth ratio. Piglets fed *B. subtilis* changed the composition of their gut microbiota by having more Firmicutes and less *Escherichia coli*. The effects of food supplementation with *Bacillus subtilis* and xylo-oligosaccharides in weaned pigs were also studied by Ding et al. (2021). By raising villus height and the ratio of villus height to crypt depth in the ileum, as well as colonic concentrations of butyrate, tryptamine, and cadaverine while lowering those of skatole, dietary supplementation with *B. subtilis* enhanced the intestinal morphology of weaned pigs.

Supplementing feed with *Saccharomyces cerevisiae* has been shown to increase feed digestibility and efficiency. Moreover, it has been demonstrated that adding yeast to meals can alter the intestinal microbiota of animals and prevent bacterial infections from colonizing the gastrointestinal system. After supplementation with *Saccharomyces*, Wang et al. (2016b) discovered a reduced ileal myeloperoxidase activity and a greater ratio of villus height to crypt depth in the ileum of broiler chickens. According to a different study by Muthusamy et al. (2011), adding saccharomyces to broiler chicken feed enhanced villus height in the jejunum, villus width in the ileum, and the number of goblet cells in the villi of the jejunum and ileum.

Probiotics on Sustainability Animal nutrition with probiotics has been recognized as a potential contributor to sustainability in the livestock industry. The use of probiotics in animal feed can help improve the overall health and productivity of livestock, reduce the use of antibiotics, and reduce greenhouse gas emissions from manure. Probiotics, as already noted, are live microorganisms that, when consumed, provide a health benefit to the host. In the context of animal nutrition, probiotics are added to feed in order to improve digestive health and overall gut function. This can lead to improved feed efficiency, reduced incidences of diseases, and better growth performance. For example, a study by Kim et al. (2015b) found that supplementing the diets of pigs with a probiotic improved their growth performance and reduced the incidence of diarrhea. One of the biggest challenges facing the livestock industry today is the increasing use of antibiotics in animal feed, due to the threat of diseases and other health issues. The overuse of antibiotics in animal feed has led to the development of antibiotic-resistant bacteria, which pose a serious threat to human health. By improving gut health and reducing the incidence of diseases, the use of probiotics in animal feed can help reduce the need for antibiotics. Another study by Pérez-Maldonado et al. (2017) found that supplementing broiler chicken diets with a probiotic reduced the need for antibiotics and improved the birds' overall health and growth performance. Another benefit of using probiotics in animal feed is the reduction of greenhouse gas emissions from manure. The use of probiotics can improve the overall digestive function of livestock, leading to better nutrient utilization and reduced waste. This, in turn, can lead to lower methane emissions from manure, as less feed is excreted in the feces. A study by Ying et al. (2017) found that supplementing the diets of dairy cows with a probiotic reduced methane emissions from manure by 11%. In conclusion, the use of probiotics in animal feed can play a significant role in improving the sustainability of the livestock industry. By improving animal health and reducing the use of antibiotics, as well as reducing greenhouse gas emissions from manure, the use of probiotics can help create a more sustainable and responsible industry.

3 Prebiotics

History Glenn Gibson and Marcel Roberfroid initially presented the idea of prebiotics in 1995. The first definition of prebiotic was given as “a non-digestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon and thus improves host health.” This criterion limits the substances that may be categorized as prebiotics in the carbohydrate class to a select few, including lactulose, GOS, and the short and long-chain fructans (FOS and inulin). So, 15 years later, at the sixth Meeting of the International Scientific Association of Probiotics and Prebiotics (ISAPP), prebiotics were defined as “a selectively fermented ingredient that results in specific changes in the composition and/or activity of the gastrointestinal microbiota, thus conferring benefit(s) upon host health” (Gibson et al. 2010).

Prebiotics can be divided into several groups based on their chemical structure and their target bacterial groups in the gut. Some common groups of prebiotics include:

- *Fructooligosaccharides (FOSs)*
- *Galactooligosaccharides (GOSs)*
- *Xylooligosaccharides (XOSs)*
- *Mannooligosaccharides (MOSs)*
- *Other Oligosaccharides*: Pectic oligosaccharide (POS) and trans-galactooligosaccharides (TOSs)

Mechanism of Action The majority of prebiotics are not digested or absorbed in the small intestine but instead are rapidly and efficiently fermented by bacteria in other sections of the alimentary canal, encouraging the growth of beneficial bacteria like *Lactobacillus* and *Bifidobacterium*. It is also noteworthy to note that a process known as “cross-feeding” occurs when the metabolism of dietary fibers, mostly prebiotics, from certain microorganisms indirectly promotes the growth of others, and the byproducts of fermentation serve as a fuel for the development of more bacteria. For instance, *Bifidobacteria* and *Lactobacilli*, which are the main fructan consumers, produce lactate and acetate during fermentation, which can be utilized by other bacteria as an energy source.

Fructooligosaccharide (FOS) A fructooligosaccharide is a special type of water-soluble carbohydrate. They include short fructose chains that the body is unable to break down. FOS is commonly used as a prebiotic in the animal diet. Some plants, such asparagus, onions, leeks, soybeans, wheat, tomatoes, and garlic, naturally contain FOS. It can provide food for probiotic microorganisms when included in a probiotic formula. According to studies, hazardous bacteria including *Salmonella*, *Clostridium perfringens*, and other food-borne diseases can be suppressed with the use of FOS. Prebiotics like FOS can indirectly aid in preventing the growth of dangerous bacteria by promoting the growth of probiotic bacteria, maintaining a healthy balance of bacteria in the gut. FOS can also improve the body's absorption of calcium, which is good for bone health. Inulin is the most well-known fructooligosaccharide. Prebiotic additives like inulin are frequently utilized in the diets of farm animals and pets. This fructooligosaccharide promotes the growth and development of friendly bacterial species that live in the large intestine, demonstrating a positive impact on host health.

Research on the effects of inulin and fructooligosaccharide on the microbiota of the gastrointestinal tract, as well as the health and productivity of animals, has increased in recent years. FOS affect the intestinal bacterial microflora of chickens, which results in an increase in *Lactobacillus* populations and a decrease in the colonies of the following bacterial species: *Salmonella*, *Campylobacter*, and *Escherichia coli* (Xu et al. 2003). Recently, similar results were discovered when FOS was utilized in broiler chicken feeds. Pathogenic bacteria including *Helicobacter* and *Desulfovibrio* were shown to be greatly decreased (Shang et al. 2018). The shape of the intestines can be positively impacted by the inclusion of inulin and fructooligosaccharide in poultry diets. The small intestine has undergone positive alterations that have enhanced its growth and improved the intestinal villus system. Inulin supplementation of formulated broiler chicken feed resulted in an increased intestinal villus length and crypt depth (Rehman et al. 2007). According to Xu et al. (2003), fructooligosaccharide supplementation significantly improved intestinal morphology, particularly where there was a higher villus-to-crypts ratio. The same type of modification was seen by Shang et al. (2015), where fructooligosaccharide (FOS) supplementation resulted in a considerable increase in villus height, crypt depth, and total mucosa thickness in the ileum of broiler chickens.

Furthermore, studies have indicated that adding fructooligosaccharide to complex chicken diets can increase production and have an impact on the chickens' overall performance. Rebolé et al. (2010) investigated the impact of inulin on broiler chicken growth performance and reported that animals fed inulin-containing diets showed noticeably better final body weight gain. Supplementing laying hens with inulin and oligofructose has also been shown to have positive effects. Increased egg production and weekly increases in total egg weight were the results of this treatment (Chen et al. 2005).

Since the commencement of aquaculture industry, one of the key goals has been to enhance fish growth and feed efficiency, which might be accomplished by improving fish nutrition and metabolism. Improvements in fish nutrition will result in improved fish health and productivity, as well as a decrease in the environmental impact of aquaculture. The use of FOS as a feed supplement in aquaculture nutrition yields good results. Fish research has mostly focused on the effects of FOS on growth performance, immunological response, and illness resistance (Grisdale-Helland et al. 2008; Ye et al. 2011; Ortiz et al. 2013). There are several studies that indicate that administering FOS produces excellent results. Hu et al. (2019)

investigated the use of FOS in the shrimp nutrition and found that FOS increased microbial diversity and reduced various potential infections in shrimp intestines, including *Vibrio tubiashii*, *Vibrio parahaemolyticus*, and *Photobacterium damselae* like strains. Paz et al. (2019) reported similar findings in which FOS boosted circulating white blood cells and accelerated phagocytosis in fish infected with *Aeromonas hydrophila*. The addition of FOS resulted in not only a stronger immune response, but also improved performance parameters such as growth rate, ultimate body mass, weight gain, and feed efficiency. In two more trials, FOS supplementation was found to increase growth, nutritional utilization, immunological and antioxidant parameters, digestive enzyme activity, gut health, and disease resistance against *Aeromonas hydrophila* (Poolsawat et al. 2020; de Campos et al. 2022). All in all, the use of FOS has produced positive outcomes in aquaculture performance and immunological measures, particularly against *Aeromonas hydrophila*.

The use of FOS in swine diet has shown excellent results. Le Bourgot et al. (2016) discovered that FOS diet boosted anti-influenza IgA levels in postweaning pig serum, indicating that it can improve vaccination response and promote growth. Schokker et al. (2018) later discovered that daily oral treatment of FOS to suckling pigs had a distinct "bifidogenic" impact, with considerable changes in microbiota composition and diversity. With these data, Le Bourgot et al. (2019) showed that FOS generated a lasting alteration of the makeup of the fecal microbiota and elevated the *Prevotella* genus. More recent research has focused on the use of FOS in piglet diarrhea occurrences, and the results revealed that FOS reduced the incidence of pig diarrhea, which linked favorably with an increase in the abundance of *Lactobacillus* and *Bifidobacterium* in the gut (Zhang et al. 2022).

The use of FOS in companion animals is being studied for the benefits it can provide to the immune system and digestive health. Nowadays, it is critical to establish dietary methods targeted at positively affecting the intestinal health of companion animals. In one research, FOS was shown to reduce insulin resistance in obese dogs, which may aid in the prevention of type 2 diabetes (Respondek et al. 2008). In another study, FOS was found to lower blood cholesterol in dogs (Jeusette et al. 2004). Pinna et al. (2016) evaluated the effect of FOS on canine fecal microbiota metabolism and discovered that FOS reduced ammonia and resulted in greater concentrations of total volatile fatty acids. The study concluded that FOS may enhance canine intestinal microbiota metabolism.

Galactooligosaccharides (GOS) GOS are a type of prebiotic fiber, composed of short chains of galactose sugars. They are not digestible by animal digestive enzymes, but they serve as food for beneficial gut bacteria, specifically *Bifidobacteria*, promoting their growth and improving gut health. GOS are commonly used as a food ingredient and can be found in some dietary supplements. In animal nutrition, galactooligosaccharides (GOS) have been shown to have several potential benefits, including:

- Improved gut health: As prebiotics, GOS can help promote the growth of beneficial gut bacteria, which can improve gut health and reduce the risk of gastrointestinal disorders.
- Enhanced immune function: By promoting the growth of beneficial gut bacteria, GOS can also help boost the immune system, helping animals to better resist infections and other diseases.
- Improved nutrient absorption: By improving gut health and reducing inflammation, GOS may also enhance the absorption of nutrients from the diet, leading to improved growth and overall health in animals.
- Reduced risk of obesity: Some studies have suggested that GOS may help regulate metabolism and reduce the risk of obesity in animals. A study published in the British Journal of Nutrition in 2009 found that GOS supplementation reduced body weight gain and improved insulin sensitivity in rats, suggesting a potential role in preventing obesity and related metabolic disorders (Kim et al. 2009).

It is important to note that more research is needed to fully understand the impact of GOS on animal nutrition and health, and the effects may vary depending on the species and individual animal.

Galactooligosaccharides have been used in broiler nutrition to enhance gut health and improve performance. Supplementing the diets of broiler chickens with GOS has been shown to reduce gut inflammation, improve gut health, and enhance growth performance in several studies. For example, a study published by Ma et al. (2010) found that broiler chickens that were fed diets supplemented with GOS showed improved gut health and reduced gut inflammation and had better growth performance compared to a control group that did not receive GOS. Another study found that supplementing the diets of layer hens with GOS improved egg quality, reduced gut inflammation, and enhanced gut health compared to a control group that did not receive GOS. The GOS-supplemented hens had higher eggshell thickness and eggshell strength and lower levels of gut inflammation markers (Yang et al. 2014). Furthermore, Wang et al. (2012) discovered that supplementing broiler chicken diets with GOS improved gut health, decreased gut inflammation, and increased growth performance when compared to a control group that did not receive GOS. GOS supplementation was also observed to modify the gut microbiota, boosting the number of good bacteria such as *Lactobacillus* and *Bifidobacterium*. Zhang et al. (2013) discovered the same results, namely that supplementing broiler chicken diets with GOS improved gut health, decreased gut inflammation, and boosted growth performance when compared to a control group that did not receive GOS. These studies provide additional evidence of the potential benefits of GOS in chicken nutrition, but more research is needed to fully understand the effects and determine the most effective dosages for different species and conditions.

In aquaculture nutrition, they can be used as a prebiotic to promote the growth of beneficial gut bacteria in fish and shellfish. This can improve the digestive health and overall immunity of the cultured species, leading to better growth performance and survival rates. However, it is important to note that the nutritional requirements of different species of fish and shellfish may vary and the use of GOS in aquaculture diets should be carefully evaluated for each species based on its nutritional requirements and potential for interactions with other dietary components. In general, research has shown that the supplementation of GOS in the diets of fish and shellfish can have positive effects on gut health, digestion, and immunity. Studies on rainbow trout, for example, have demonstrated that adding GOS to the diet can improve gut microbiota, increase nutrient utilization and growth performance, and lower disease susceptibility. Similarly, GOS supplementation has been shown in experiments on Pacific white shrimp to improve the gut flora, increase growth and survival, and reduce illness incidence (Kim et al. 2016). Other studies have shown that GOS can be a beneficial supplement in the diets of other aquaculture species such as Atlantic salmon and tilapia. Particularly, Chen et al. (2017) found that the supplementation of GOS in the diet of Nile tilapia improved growth performance, increased the abundance of beneficial gut bacteria, and enhanced the non-specific immune responses of the fish. Specifically, the tilapia fed a diet containing GOS showed a significant increase in weight gain and feed efficiency compared to those fed a control diet without GOS. The study also found that GOS supplementation significantly altered the gut microbiota composition, increasing the relative abundance of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium*, and reducing the relative abundance of potentially pathogenic bacteria. Furthermore, the study found that GOS supplementation improved the non-specific immune responses of Nile tilapia, as indicated by increased levels of lysozyme activity and phagocytic activity. Overall, the results of this study suggest that GOS can be a beneficial supplement for Nile tilapia, improving growth performance, gut health, and immunity. Same results were reported by Lee et al. (2015a) which showed that supplementation of GOS in the diet improved the growth performance of Atlantic salmon, with fish fed a diet containing GOS exhibiting a significant increase in weight gain and feed efficiency compared to those fed a control diet without GOS. The study also found that GOS supplementation led to an increase in the activity of digestive enzymes such as amylase, lipase, and protease, indicating improved digestive health in the fish. Furthermore, the study found that GOS supplementation altered the gut microbiota of Atlantic salmon, with the relative abundance of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium* increased, while the relative abundance of potentially pathogenic bacteria was reduced.

Galactooligosaccharides have been studied for their potential benefits in swine nutrition. Some research has shown that GOS can improve gut health by promoting the growth of beneficial bacteria, leading to improved feed efficiency, weight gain, and overall health in swine. Other studies have also reported improved gut barrier function, reduced diarrhea and improved nutrient digestibility in swine fed diets containing GOS. However, the results of these studies are mixed, and more research is needed to fully understand the effects of GOS in swine nutrition and determine the optimal levels for use in pig diets. More specifically, a study conducted by Zhang et al. (2015) revealed that supplementing the diets of weanling pigs with galactooligosaccharides had effects on growth performance, with pigs fed diets containing GOS having improved average daily gain and feed conversion ratio compared to control pigs; nutrient digestibility, with pigs fed diets containing GOS having increased digestibility of crude protein, crude fat, and dry matter and in fecal bacterial populations, where the researchers found changes in the populations of fecal bacteria, with an increase in the numbers of *Bifidobacteria* and *Lactobacilli*. Sun et al. (2016) later explored the effects of supplementing weaned pig diets with galactooligosaccharides (GOS) on gut health and gut microbiota in pigs challenged with *E. coli*. Pigs fed GOS-containing diets demonstrated improved indicators of gut health, including lower diarrhea scores, improved intestinal morphology, and lower levels of pro-inflammatory cytokines in the gut. Furthermore, there was evidence that feeding GOS to pigs changed the makeup of their gut microbiota, with an increase in the numbers of helpful bacteria like *Lactobacilli* and *Bifidobacteria* and a decrease in the numbers of harmful bacteria like *E. coli*. Another study investigated the effects of GOS supplementation on growth performance, nutrient digestibility, and gut microbiota of growing pigs. The results showed that GOS supplementation improved the average daily gain and average daily feed intake of the pigs. The apparent total tract digestibility of dry matter and crude protein was also increased. In terms of gut microbiota, the study found that GOS supplementation led to an increase in the population of beneficial bacteria such as *Lactobacillus* and a decrease in the population of harmful bacteria such as *Escherichia coli* (Cui et al. 2019). Same results were found by Ma et al. (2020) on the gut environment and gut microbiota of growing-finishing pigs. The results showed that GOS supplementation increased the populations of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium* in the gut of the pigs and decreased the population of harmful bacteria such as *Escherichia coli*. In terms of gut environment, the study found that GOS supplementation reduced the pH of the hindgut and increased the concentrations of short-chain fatty acids, particularly acetate and propionate. Overall, the results of this study suggest that GOS supplementation has the potential to improve the gut environment and modulate the gut microbiota in a beneficial direction in growing-finishing pigs. To sum up, galactooligosaccharides (GOS) can improve gut health and modulate gut microbiota in swine. GOS supplementation has resulted in improved feed efficiency, weight gain, and gut health in weanling and growing pigs, with increased growth performance and nutrient digestibility, and changes in the populations of fecal bacteria, such as an increase in the numbers of *Bifidobacteria* and *Lactobacilli* and a decrease in harmful bacteria like *E. coli*. The gut environment was also improved, with decreased pH of the hindgut and increased concentrations of short-chain fatty acids. More research is needed to fully understand the effects of GOS in swine nutrition.

Several studies have explored the use of galactooligosaccharides as a supplement in ruminant nutrition. The results of these studies have been mixed, with some finding positive effects on growth performance, feed efficiency, and gut health in ruminants, while others have found no significant effects. Rondina et al. (2017) investigated the use of GOS in dairy heifers' nutrition. The results of this study showed that dietary supplementation with GOS improved growth performance and feed efficiency in dairy heifers, as well as increased total tract digestibility of dry matter, organic matter, and neutral detergent fiber. Ma et al. (2017) used galactooligosaccharides in lambs' nutrition. In this study, lambs showed improved growth performance and feed efficiency, as well as increased nutrient digestibility. The researchers also found changes in ruminal fermentation, with an increase in the populations of beneficial bacteria such as *Lactobacillus* and a decrease in the populations of harmful bacteria such as *Escherichia coli*. Last, Lu et al. (2017) investigated the effects of GOS in sheep nutrition. The results of this study showed that dietary supplementation with GOS improved growth performance and feed efficiency in sheep, as well as increased nutrient digestibility and rumen pH. These studies suggest that GOS supplementation may have potential benefits for ruminants, such as improved growth performance, feed efficiency, and gut health. However, more research is needed to fully understand the effects of GOS in ruminant nutrition and determine the optimal levels for use in ruminant diets.

Xylooligosaccharides (XOS) Xylooligosaccharides are short chains of xylose sugars that can act as prebiotics in the gut. They are a type of oligosaccharide, which are carbohydrates made up of a small number of sugar units, typically two to ten. XOS are fermented by certain strains of bacteria in the gut, producing short-chain fatty acids (SCFAs) that can have beneficial effects on the host. XOS have been shown to increase the populations of beneficial bacteria such as *Bifidobacteria* and *Lactobacilli* in the gut, which can help to maintain gut health and improve overall gut microbiome diversity. They have also been reported to improve gut health and digestive function, boost the immune system, and promote mineral absorption. XOS supplementation has been shown to improve growth performance and nutrient digestibility in livestock animals and has potential applications in companion animal diets (Van Laere et al. 2010). Overall, XOS is a promising prebiotic with multiple potential health benefits. However, more research is needed to fully understand the effects of XOS on gut health and the optimal levels for use in animal diets.

Xylooligosaccharides are a type of prebiotic that have been studied for their potential benefits in chicken nutrition. XOS are derived from xylose, a sugar found in many plant materials and have been shown to promote the growth of beneficial bacteria in the gut. This can lead to improved gut health, which can have a positive impact on a chicken's overall health and performance. Studies have investigated the effects of XOS supplementation on various aspects of chicken nutrition, including growth performance, nutrient digestibility, and gut health. In one study, XOS supplementation was found to improve the growth performance and feed conversion efficiency of broiler chickens (Wang et al. 2019c). Another study found that XOS supplementation improved the digestibility of nutrients, such as crude protein and crude fat, in chickens (Zhao et al. 2018). In addition to improving growth performance and nutrient digestibility, XOS supplementation has also been found to improve gut health in chickens. For example, one study found that XOS supplementation reduced the levels of harmful bacteria in the gut of broiler chickens, while promoting the growth of beneficial bacteria (Ren et al. 2018). This can lead to improved gut barrier function, which can help to reduce the risk of enteric infections, such as *Escherichia coli* and *Salmonella* spp. Overall, these findings suggest that

XOS may be a useful addition to chicken diets for improving growth performance, nutrient digestibility, and gut health.

In aquaculture feeding XOS can improve gut health and growth performance in fish. XOS are oligosaccharides, which are short-chain carbohydrates digested by gut bacteria to create short-chain fatty acids (SCFAs). SCFAs have been proven to improve gut health by increasing the abundance of beneficial gut bacteria, decreasing the quantity of potentially pathogenic bacteria, and enhancing gut barrier function. One study investigated the effects of XOS supplementation on growth performance and gut microbiota of Pacific white shrimp (*Litopenaeus vannamei*). The results showed that XOS supplementation significantly improved the weight gain and feed efficiency of the shrimp compared to the control group. Additionally, XOS supplementation altered the gut microbiota composition, increasing the relative abundance of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium*, and reducing the relative abundance of potentially pathogenic bacteria (Zhang et al. 2019). Another study investigated the effects of XOS supplementation on the growth performance, non-specific immunity, and gut microbiota of Pacific white shrimp. The results showed that XOS supplementation significantly improved weight gain and feed efficiency, and enhanced non-specific immune responses, as indicated by increased levels of hemolymph phenoloxidase activity and superoxide dismutase activity. Furthermore, XOS supplementation altered the gut microbiota composition, increasing the relative abundance of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium*, and reducing the relative abundance of potentially pathogenic bacteria (Liu et al. 2019). One more study on the use of XOS in aquaculture nutrition is made by Chen et al. (2018) showed that xylooligosaccharides supplementation improved the growth performance, increased the activities of digestive enzymes and altered the gut microbiota composition of Nile tilapia. Specifically, the study found that supplementing the diet with XOS increased the weight gain, specific growth rate, and feed efficiency of Nile tilapia. The activities of digestive enzymes, such as trypsin, lipase, and amylase, were also enhanced in tilapia fed with xylooligosaccharides. The study also observed that the gut microbiota of tilapia fed with XOS was more diverse and had a higher proportion of beneficial bacteria, such as *Lactobacillus*. In conclusion, XOS have shown potential as a beneficial supplement for aquaculture, improving growth performance and gut health in fish and shrimp species. Further research is needed to fully understand the optimal concentration and effects of XOS in aquaculture, and to determine if the benefits observed in laboratory studies can be replicated in commercial-scale aquaculture systems. However, the results of the studies suggest that XOS have potential as a prebiotic for the promotion of gut health and growth performance in aquaculture.

Xylooligosaccharides have been proven in studies to increase swine growth performance, nutritional digestibility, and gut health. XOS supplementation can enhance the number of helpful gut bacteria like *Lactobacillus* and *Bifidobacterium* while decreasing the number of dangerous bacteria like *E. coli* and *Salmonella* spp. This can result in better gut health and a lower risk of enteric infections. One study conducted by Li et al. (2017b) found that XOS supplementation significantly improved the average daily gain and feed conversion efficiency of growing-finishing pigs. In addition, XOS supplementation was found to improve nutrient digestibility, including crude protein and gross energy. Another study by Chen et al. (2017) found that XOS supplementation improved gut health by reducing gut inflammation and increasing the number of beneficial bacteria. This was associated with improved growth performance, including higher average daily gain and improved feed conversion efficiency. These findings suggest that XOS can play an important role in improving the health and performance of swine. Last Zeng et al. (2018) found that supplementation of xylooligosaccharides improved the growth performance and nutrient digestibility of weaning pigs. The authors also found that xylooligosaccharides supplementation had a positive effect on the intestinal health of the pigs, as indicated by improved gut barrier function and reduced oxidative stress. From all these information, it can be deduced that Xylooligosaccharides (XOS) supplementation has a positive effect on the growth performance and gut health of swine. XOS supplementation can also be associated with improved gut barrier function and reduced oxidative stress in weaning pigs.

In ruminants, studies have shown that supplementing their diet with XOS can improve the growth performance and feed efficiency of the animals. For example, a study by Sun et al. (2017) showed that supplementation of XOS in the diet of beef cattle increased average daily gain and feed efficiency. Another study by Li et al. (2019a) found that adding XOS to the diet of dairy cows increased milk yield and improved feed conversion efficiency. XOS also have positive effects on gut health in ruminants. By selectively promoting the growth of beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, XOS can help to maintain a healthy gut microbiota, reduce the risk of digestive disorders and improve animal health. A study by Liu et al. (2018) found that supplementing the diet of dairy cows with XOS reduced the incidence of subacute ruminal acidosis and improved feed digestibility. To sum up, xylooligosaccharides have been found to have positive effects on the growth performance and gut health of ruminants.

In companion animals, several studies have investigated the effects of XOS supplementation in their diets. In one study, the addition of XOS to the diets of dogs was found to increase the population of *Bifidobacteria* and *Lactobacilli* in the gut, which are considered to be beneficial bacteria (Couturier et al. 2011). In another study, the addition of XOS to the diets of cats was shown to improve gut health, as measured by an increased population of beneficial bacteria and a reduction in gut pH (Chou et al. 2018). XOS supplementation has also been shown to improve nutrient utilization in companion animals. In the same studies as before, the addition of XOS to the diets of dogs was found to increase the digestibility of protein and fat (Couturier et al. 2011). In the other study, the addition of XOS to the diets of cats was shown to improve the digestibility of starch and dietary fiber (Chou et al. 2018). In conclusion, Xylooligosaccharides are a promising nutritional supplement for companion animals, as they have been shown to improve gut health, support the immune system, and increase nutrient utilization.

Mannooligosaccharides (MOS) Are a type of prebiotic that are made up of short chains of mannose, a type of sugar. They are naturally found in some plants and have been found to have a number of health benefits when consumed. They are composed of short chains of mannose sugars and have a molecular weight of less than 1000 Daltons, which makes them highly soluble in water. The chain length of MOS varies and ranges from two to six mannose residues. MOS is attracting increasing attention as a dietary ingredient for animals because of its potential to improve gut health and overall performance. MOS works by selectively promoting the growth and activity of beneficial bacteria in the gut, thereby helping to maintain a healthy gut microbiome. This is important in animal nutrition, as the gut microbiome has been found to play a key role in many aspects of animal health and performance, including the digestion and absorption of nutrients, the immune response, and the prevention of disease. In addition to their prebiotic effects, MOS has also been found to have a number of other benefits in animal nutrition, including improved growth performance, increased nutrient digestibility, and reduced incidence of gut-related diseases. As a result, MOS is being increasingly used as a dietary ingredient in animal feed, particularly for poultry and swine. These findings suggest that MOS has the potential to play an important role in improving the health and performance of animals and may provide a promising alternative to other types of prebiotics and antibiotics.

Mannooligosaccharides (MOSs) are a type of prebiotic that are used in chicken nutrition to improve gut health and performance. MOS is a type of oligosaccharide derived from mannan, a naturally occurring polysaccharide found in the cell walls of yeast and other fungi. MOS is known to have several beneficial effects on gut health and function, including promoting the growth of beneficial bacteria and reducing the growth of pathogenic bacteria. Studies have shown that MOS supplementation in chickens can improve growth performance, feed conversion efficiency, and immune function. For example, a study conducted by Hong et al. (2017) found that supplementing chicken diets with MOS improved average daily gain and feed conversion efficiency compared to control groups. The authors also found that MOS supplementation improved immune function, as indicated by increased antibody production, and improved disease resistance. Another study by Tan et al. (2015) found that MOS supplementation in chickens was associated with an increased population of beneficial bacteria in the gut, including *Lactobacillus* and *Bifidobacterium* species. The authors also found that MOS supplementation reduced the presence of harmful bacteria, including *Escherichia coli* and *Salmonella* spp. These findings suggest that MOS can play an important role in maintaining gut health and reducing the risk of disease in chickens. In addition to improving gut health and performance, MOS supplementation has also been shown to have positive effects on nutrient digestibility and utilization in chickens. For example, a study conducted by Wang et al. (2017a) found that MOS supplementation improved nutrient digestibility, including crude protein and gross energy. The authors also found that MOS supplementation was associated with improved gut function, including increased intestinal villi length and reduced gut inflammation. These findings suggest that MOS can play an important role in optimizing nutrient utilization and improving overall health and performance in chickens.

In the nutrition of aquaculture MOS have been widely studied for their benefits to gut microbiota and digestive health, leading to better growth performance, feed utilization, and disease resistance in aquaculture species. Studies have shown that MOS supplementation in aquaculture diets can improve growth performance and feed utilization in fish and crustaceans. For example, a study by Wang et al. (2017b) found that MOS supplementation in the diet of grass carp improved growth performance and nutrient utilization. Another study by Zhang et al. (2019c) reported that MOS supplementation in the diet of white shrimp improved feed utilization and growth performance. Gut health is critical for the overall health and performance of aquaculture species, and MOS supplementation has been shown to improve gut health and reduce the risk of disease in fish and crustaceans. For instance, a study by Li et al. (2018a) found that MOS supplementation in the diet of black carp improved gut health and reduced the risk of disease. Another study by Chen et al. (2019b) reported that MOS supplementation in the diet of common carp improved gut microbiota, leading to improved gut health and disease resistance. In conclusion, MOS supplementation in aquaculture diets has been shown to improve growth performance, feed utilization, and gut health in fish and crustaceans. The benefits of MOS supplementation in aquaculture nutrition have been demonstrated in multiple studies, providing evidence for its use in the aquaculture industry.

In swine nutrition MOS can improve gut health and performance including promoting the growth of beneficial bacteria and reducing the growth of pathogenic bacteria. Studies have shown that MOS supplementation in swine can improve growth performance, feed conversion efficiency, and nutrient digestibility. For example, a study conducted by Li et al. (2018b) found that supplementing swine diets with MOS improved average daily gain and feed conversion efficiency compared to control groups. The authors also found that MOS supplementation improved nutrient digestibility, including crude protein and gross energy. Another study by Chen et al. (2019a) found that MOS supplementation in swine was associated with an increased population of beneficial bacteria in the gut, including *Lactobacillus* and *Bifidobacterium* species. The authors also found that MOS supplementation reduced the presence of harmful bacteria, including *Clostridium* and *Escherichia coli*. These findings suggest that MOS can play an important role in maintaining gut health and reducing the risk of disease in swine. In addition to improving gut health and performance, MOS supplementation has also been shown to have positive effects on gut morphology and function in swine. For example, a study conducted by Zeng et al. (2019) found that MOS supplementation improved gut barrier function and reduced oxidative stress. The authors also found that MOS supplementation was associated with improved gut morphology, including increased intestinal villi length and reduced gut inflammation. These findings suggest that MOS can play an important role in optimizing gut function and improving overall health and performance in swine.

MOS has been also shown to have a number of potential benefits in ruminant nutrition, including improved gut health, increased feed efficiency, and enhanced animal performance. One of the key mechanisms by which MOS works is by supporting the growth of beneficial gut bacteria and inhibiting the growth of harmful bacteria. This helps to maintain a healthy gut microflora and reduce the risk of digestive disorders, such as diarrhea, that can impact animal performance. MOS has also been shown to improve feed efficiency in ruminants by reducing the amount of feed that is passed undigested through the gut, thus increasing the overall nutrient utilization. Several studies have investigated the effects of MOS on ruminant performance, and the results have been generally positive. In one study, the effect of mannanoligosaccharides on performance, fecal characteristics, and cecal volatile fatty acid concentrations in young bulls was investigated. The results showed that mannanoligosaccharide supplementation improved feed efficiency, had a positive effect on fecal characteristics, and increased the concentration of propionic acid in the cecum (Rodehutscord et al. 2001). Furthermore, De Boever et al. (2005) discovered that feeding MOS to lambs enhanced feed conversion rates and boosted live weight growth. Another study, by Bélanger et al. (2010), found that MOS supplementation enhanced feed efficiency and milk output in dairy cows. In conclusion, the use of Mannooligosaccharides in ruminant nutrition has shown promising results in terms of improved gut health, increased feed efficiency, and enhanced animal performance.

Other Oligosaccharides Pectic-oligosaccharides and trans-galactooligosaccharides are two types of dietary oligosaccharides that have received attention for their potential use in animal nutrition. These oligosaccharides are non-digestible by the host animal and thus they can reach the gut microbiome where they may provide various benefits. Pectic-oligosaccharides (POSs) are oligomers derived from the breakdown of pectin; a type of polysaccharide found in plant cell walls. These oligosaccharides are known for their prebiotic properties, meaning that they selectively promote the growth and activity of beneficial gut microbes. They have been shown to improve gut health by increasing the populations of *Bifidobacteria* and *Lactobacilli*, and by reducing the populations of harmful bacteria such as *E. coli* and *Salmonella*. For example, a study by Pan et al. (2012) investigated the effects of pectic-oligosaccharides supplementation in weanling pigs and found that they improved gut health and reduced the populations of harmful bacteria in the gut.

Similarly, trans-galactooligosaccharides (TOSs) are prebiotic compounds derived from lactose. They have been shown to increase the populations of *Bifidobacteria* and *Lactobacilli* in the gut and to reduce the populations of harmful bacteria. In addition, they have been shown to improve gut health by improving the gut barrier function and reducing gut inflammation. Fan et al. (2017) investigated the effects of TOS supplementation in broiler chickens and found that it improved gut health and increased the populations of beneficial bacteria in the gut. All in all, POS and TOS have shown promise as potential dietary supplements in animal nutrition. However, more research is needed to fully understand their effects and to determine the optimal levels of supplementation for different species and production systems.

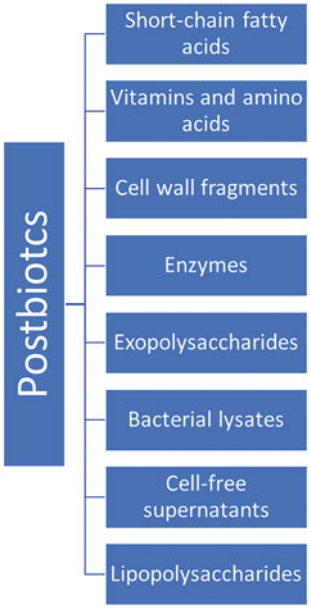
Prebiotics on Sustainability The use of prebiotics in animal nutrition has been shown to have a positive impact on animal health, productivity, and sustainability in animal production. One of the benefits of using prebiotics in animal nutrition is the improvement of gut health and digestive function. The growth of beneficial bacteria in the gut helps to maintain a healthy gut environment and to support the digestion and absorption of nutrients. This can lead to improved feed efficiency, which in turn can reduce the amount of feed required to produce a unit of animal product, and ultimately reduce the environmental impact of animal production. For example, a study by O'Doherty et al. (2017) found that supplementing the diets of dairy cows with a prebiotic improved feed efficiency and reduced the amount of nitrogen excreted in manure. Another benefit of using prebiotics in animal nutrition is the reduction of the use of antibiotics. Antibiotics are often used in animal production to prevent and treat diseases, but the overuse of antibiotics can lead to the development of antibiotic-resistant bacteria, which pose a serious threat to human health. The use of prebiotics in animal feed has been shown to improve gut health and reduce the incidence of diseases, which can help to reduce the need for antibiotics. For example, a study by Kumprecht et al. (2015) found that supplementing the diets of broiler chickens with a prebiotic reduced the need for antibiotics and improved the birds' overall health. The use of prebiotics can also have a positive impact on the environment by reducing greenhouse gas emissions from manure. The growth of beneficial bacteria in the gut can lead to improved nutrient utilization, reducing the amount of waste excreted in feces, and ultimately reducing the amount of methane produced from manure. A study by Wang et al. (2017) found that supplementing the diets of beef cattle with a prebiotic reduced methane emissions from manure by 9%. To sum up, the use of prebiotics in animal nutrition can contribute significantly to sustainability in animal production. By improving animal health and reducing the use of antibiotics, as well as reducing greenhouse gas emissions from manure, the use of prebiotics can help create a more sustainable and responsible industry.

4 Paraprobiotics and Postbiotics

History The concept of paraprobiotics and postbiotics as a means of promoting health in the gut is relatively new, but the use of probiotics and other gut-microbe-related interventions is a long-standing field of study. The terms "paraprobiotics" and "postbiotics" have been introduced to describe new approaches to gut health. Paraprobiotics are a class of functional food ingredients that are similar to probiotics but lack the capacity to colonize the host gut. They are typically derived from prebiotic compounds or inactivated probiotics and act by selectively promoting the growth and activity of beneficial gut bacteria, thereby modulating the gut microbiome and improving gut health. Unlike probiotics, paraprobiotics are not living organisms, making them more stable and easier to handle during storage and processing. These compounds have been shown to enhance gut health by increasing the abundance of beneficial bacteria and reducing the growth of harmful bacteria, thereby improving gut functionality and overall animal health (Wang et al. 2019a).

Postbiotics refer to the metabolic by-products of probiotics, some examples of postbiotics include short-chain fatty acids (SCFAs) such as acetate, propionate, and

Fig. 3 Types of postbiotics



butyrate, bacteriocins, lipopolysaccharides, and host-derived peptides that are produced during the fermentation of probiotics. They play a crucial role in maintaining gut health by regulating the balance of gut microbiota and influencing the host's immune system. Unlike probiotics, postbiotics do not require live bacteria to be present for their benefits to be realized. Postbiotics have been shown to have a range of health benefits, including improved gut health, reduced inflammation, and improved immune function. They are also being investigated for their potential use in the treatment of a variety of diseases, including inflammatory bowel disease, irritable bowel syndrome, and colorectal cancer. Moreover, postbiotics are considered to be a promising new area of research in the field of gut health, as they offer many potential benefits without the concerns associated with live probiotics. However, more research is needed to fully understand the mechanisms by which postbiotics work and to determine the best methods for producing and delivering them in supplement form (Kim et al. 2015a) (Fig. 3).

Mechanism of Action Paraprobiotics work by altering the gut microbiota and leading to various health benefits. The mode of action of paraprobiotics can vary depending on the specific microorganism and the targeted animal species. However, some of the common mechanisms of action include stimulation of the immune system and inhibition of inflammation. Additionally, paraprobiotics can also modulate the gut environment, by producing organic acids and other metabolic by-products that can improve gut pH and affect gut permeability. These changes can enhance the stability and diversity of the gut microbiome, leading to improved gut health and animal performance (Siciliano et al. 2021).

The mechanism of action of postbiotics can vary depending on the specific substance produced, but some of the common ways that postbiotics can influence the host include:

1. Modulation of the gut environment: Certain metabolic by-products produced by gut bacteria, such as short-chain fatty acids (SCFAs) and lactic acid, can change the pH of the gut and modulate the gut environment. This can lead to improved gut health and prevent the growth of harmful bacteria.
2. Stimulation of the immune system: Some postbiotics have been shown to activate the host's immune system, leading to an increase in the production of cytokines and other immune system components. This can enhance the body's ability to fight off infections and prevent disease.
3. Antimicrobial activity: Some postbiotics have antimicrobial properties and can prevent the growth of harmful bacteria in the gut. This can improve gut health and prevent the development of digestive disorders.
4. Regulation of gene expression: Some postbiotics have been shown to influence gene expression in the host, leading to changes in metabolism and other physiological processes. This can lead to improved health and performance in animals.
5. Modulation of the gut microbiome: Postbiotics can influence the composition of the gut microbiome, leading to increased diversity and stability of gut bacteria. This can have a positive impact on gut health and animal performance.

The exact mechanism of action of postbiotics can depend on the specific substance produced, the dose and duration of treatment, and the target animal species. Additionally, further research is needed to fully understand the mechanisms by which postbiotics exert their effects (Żółkiewicz et al. 2020; Wegh et al. 2019) (Fig. 4).

Use of Para-postbiotics in the Poultry Nutrition The use of paraprobiotics and postbiotics in poultry nutrition has been a growing area of research in recent years due to their potential to improve the health and performance of poultry birds, as well as their promised ability to replace antibiotics (Abd El-Ghany 2020). In the study by Shu et al. (2018), the effects of non-viable yeast on growth performance, digestive enzyme activity, and gut microbiota of broilers were evaluated. The study found that the supplementation of non-viable yeast in the diet of broilers significantly improved their average daily gain and feed conversion ratio. The supplementation also increased the activity of digestive enzymes such as amylase, trypsin, and lipase, indicating improved digestion and nutrient utilization. Furthermore, the gut microbiota of broilers fed the non-viable yeast-supplemented diet showed increased abundance of beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, and reduced abundance of pathogenic bacteria, such as *Escherichia coli*. These results suggest that the supplementation of non-viable yeast in the diet of broilers has beneficial effects on their growth performance, digestive function, and gut health. In another study, the authors investigated the effects of feeding broiler chickens with non-viable yeast cell wall on growth performance, gut health, and immune function.

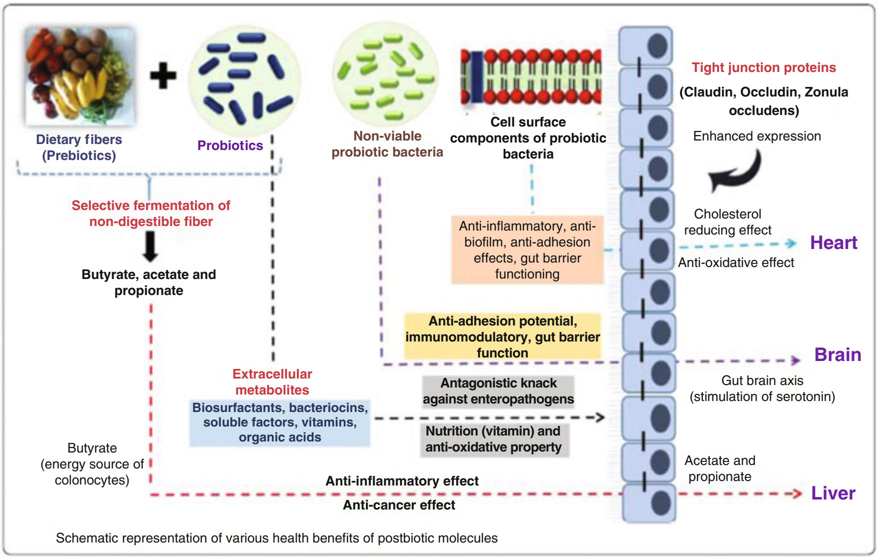


Fig. 4 Schematic representation of various benefits of postbiotic molecules

They found that the supplementation of non-viable yeast cell wall improved feed conversion ratio, enhanced gut health (by reducing the levels of harmful bacteria and increasing the populations of beneficial bacteria in the gut) and boosted the immune function of the broilers. The results of this study suggest that non-viable yeast cell wall may have potential as a nutritional supplement for improving the growth performance and gut health of broiler chickens (Liu et al. 2020). Furthermore, Lallemand Animal Nutrition (2022) made a hydrolyzed yeast that has been specifically designed to support animal performance, digestive care, and feed palatability while contributing to the feed protein balance. This hydrolized yeast can be used as a functional protein source due to its superior kinetics of protein digestibility, which starts at 77% at the beginning of the intestinal phase and increases to 94% after 48 hours. Last, a study that investigated the use of paraprobiotics in layer hen nutrition found that supplementing the diet of layer hens with non-viable yeast improved egg production and egg quality, while positively altering the gut microbiota. The authors concluded that non-viable yeast has potential as a dietary supplement in layer hen nutrition (Yong et al. 2019).

The same results were seen when postbiotics were delivered to layer chickens. As an example, consider the research by Zhang et al. (2019b). The scientists gave layer hens a meal enriched with postbiotics generated from lactic acid bacteria and discovered that the hens outperformed control birds in terms of growth performance, egg quality, and gut microbiome. The findings of this study imply that postbiotics may benefit the health and performance of layer hens. On another study made by Abd El-Ghany et al. (2022) found that the use of a postbiotic compound produced by stabilized non-viable *Lactobacilli* in the feed and drinking water of broiler chickens can have a positive impact on their health, growth performance, immunity, and resistance to *Escherichia coli* challenge. The study found that feed and water treatments with the postbiotic compound improved the disease picture, growth performance, immune response, bursa of Fabricius/body weight ratio, and reduced the intestinal coliform count in challenged chickens when compared to non-treated chickens. These results suggest that the use of the postbiotic compound in either dry or aqueous form is effective in improving the health and performance of broiler chickens and may help reduce the risk of colisepticemic disease in these birds.

Use of Para-postbiotics in the Swine Nutrition The use of paraprobiotics in swine nutrition has received increasing attention in recent years, as they offer a promising alternative to traditional antibiotic growth promoters. In one study made by Zhou et al. (2015) the authors aimed to evaluate the effects of non-viable yeast cell products on the gut microflora and growth performance of weaning pigs. The results showed that the supplementation of non-viable yeast cell products significantly increased the population of *Lactobacillus* and reduced the population of coliform bacteria in the gut of the pigs. The pigs fed the diet supplemented with high levels of non-viable yeast cell products had the highest average daily gain (ADG) and the best feed conversion ratio (FCR) compared to the control group. The authors concluded that the supplementation of non-viable yeast cell products improved the gut microflora and enhanced the growth performance of weaning pigs. Same findings were reported by Wang et al. 2018a who investigated the effects of a non-viable yeast-based product on the gut health and performance of weaning pigs. The results showed that supplementing the pigs' diet with the non-viable yeast-based product improved their weight gain and feed efficiency, as well as reduced the incidence of diarrhea. The study also demonstrated that the supplementation of the non-viable yeast-based product modulated the gut microbiota, leading to an increased abundance of beneficial bacteria and a reduced abundance of pathogenic bacteria. Finally, a study (Kim et al. 2019) evaluated the effects of a non-viable yeast product on the growth performance and gut microbiota of growing-finishing pigs. The results showed that supplementing the pigs' diet with the non-viable yeast product improved their average daily gain and feed efficiency, compared to the control group. Furthermore, the gut microbiota of the pigs fed with the non-viable yeast was found to be more diverse and had a higher proportion of beneficial bacteria compared to the control group.

As a relatively new area of research, there have not been many studies on the use of postbiotics in swine nutrition. One study that investigated the use of postbiotics, evaluated the effects of *Bacillus*-derived postbiotics on growth performance, gut morphology, and gut microbiota in growing pigs. The results showed that supplementation of postbiotics improved the average daily gain and feed efficiency of the pigs. In addition, the study found that the postbiotics treatment improved gut morphology, including villus height and crypt depth, and positively influenced the gut microbiota by increasing the abundance of beneficial bacteria and decreasing the abundance of pathogenic bacteria. The authors concluded that postbiotics could be a promising alternative to antibiotics for improving gut health and performance in growing pigs (Zhou et al. 2019b).

Use of Para-postbiotics in the Aquaculture Nutrition Paraprobiotics are increasingly being studied and used in aquaculture nutrition. The goal of using paraprobiotics in aquaculture is to promote the growth and health of fish and other aquatic species, while also reducing the use of antibiotics and other harmful chemicals. Paraprobiotics work by selectively promoting the growth of beneficial bacteria in the gut of aquatic animals, thereby modulating the gut microbiome and improving gut health. Studies have shown that the use of paraprobiotics in aquaculture can lead to improved growth performance, feed efficiency, and disease resistance in fish and other aquatic species. One study, for example, found that supplementing the diets of juvenile sea bass with a paraprobiotic mixture led to improved growth performance and feed efficiency, as well as a reduction in mortality rates (Ozkoc et al. 2016). Another study investigated the effect of a paraprobiotic containing *Lactobacillus reuteri* on the growth performance, gut microbiota, and immune response of tilapia. The results showed that the fish fed with the paraprobiotic had higher weight gain, improved feed conversion rate, and better gut microbiota compared to the control group. Additionally, the fish fed with the paraprobiotic showed an enhanced immune response, as indicated by higher levels of IgM and lysozyme activity. The authors concluded that the use of the *L. reuteri*-containing paraprobiotic has the potential to improve the growth performance, gut health, and immunity of tilapia in aquaculture (Li et al. 2019b). A third study looked at the effect of a paraprobiotic containing *Bacillus subtilis* on the growth performance, gut microbiota, and disease resistance of rainbow trout. The results showed that the dietary supplementation of the paraprobiotic significantly improved the weight gain, feed conversion ratio, and specific growth rate of the rainbow trout. Additionally, the paraprobiotic supplementation altered the gut microbiota composition, leading to an increase in the abundance of beneficial bacteria and a decrease in the abundance of harmful bacteria. Furthermore, the paraprobiotic supplementation increased the total antioxidant capacity, lysozyme activity, and interleukin-1β levels, indicating an improvement in the immune response of the rainbow trout. In conclusion, the results of the study suggest that the supplementation of a paraprobiotic containing *Bacillus subtilis* can improve the growth performance, gut microbiota, and disease resistance in rainbow trout. Zhou et al. (2019a) to sum up, the use of paraprobiotics in aquaculture is a promising approach for promoting the growth and health of fish and other aquatic species, while also reducing the use of antibiotics and other harmful chemicals. Further research is needed to fully understand the mechanisms of action and optimal use of paraprobiotics in aquaculture.

While there is a growing body of research on the use of postbiotics in other fields such as human and animal health, the use of postbiotics in aquaculture nutrition is still an emerging area of research with limited data available. Further studies are needed to establish the efficacy of postbiotics in enhancing the health and growth of aquaculture species. There is one study by Dong et al. (2020) who aimed to evaluate the effects of probiotic byproducts on growth performance, immune response, and gut microbiota of tilapia (*Oreochromis niloticus*). The study used four groups of tilapias, a control group and three treatment groups that were fed diets supplemented with different levels of postbiotics for 56 days. The results showed that the growth performance of tilapia fed diets containing postbiotics was significantly higher than the control group. The feed utilization efficiency of tilapia was also improved with increasing levels of postbiotics in the diet. The results also indicated that the postbiotics had a positive effect on the immune response of tilapia, as the serum lysozyme activity and phagocytic rate of the fish were significantly increased. In terms of gut microbiota, the results showed that the postbiotics significantly affected the abundance of certain bacteria in the gut of tilapia. The study found that the abundance of beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, was increased, while the abundance of harmful bacteria, such as *Aeromonas* and *Escherichia coli*, was reduced. Overall, the results of this study suggest that the use of postbiotics in tilapia diets can improve growth performance, enhance immune response, and positively affect gut microbiota composition.

Use of Para-postbiotics in the Ruminant Nutrition The use of paraprobiotics in ruminant nutrition has gained considerable interest in recent years due to their potential to enhance animal performance, improve gut health, and modulate the rumen microbiome. A study by Cai et al. (2020) investigated the effects of a non-viable yeast cell product on growth performance, rumen fermentation and antioxidant capacity in beef cattle. The results showed that the beef cattle fed the yeast cell product had improved average daily gain, feed conversion ratio, and rumen pH compared to the control group. The study also showed that the antioxidant capacity of the beef cattle fed the yeast cell product was increased, indicating improved rumen health, and reduced oxidative stress. Another study by Moura et al. (2017) investigated the effects of supplementing non-viable yeast cell wall extracts on performance and ruminal acidosis in dairy cows. The results showed that supplementation with non-viable yeast cell wall extracts improved dry matter intake and milk yield, increased rumen pH, and decreased lactate concentration. The study also found that supplementation with non-viable yeast cell wall extracts reduced the occurrence of subacute ruminal acidosis (SARA), a common metabolic disorder in dairy cattle. These results suggest that the use of non-viable yeast cell wall extracts can improve the performance and health of dairy cattle by maintaining ruminal pH and reducing the risk of SARA. Prior to this study van der Meijden et al. (2015) also reported that non-viable yeast cell wall extracts supplementation reduced the risk of ruminal acidosis and improved health status in dairy cows. Furthermore, non-viable yeast cell wall extracts supplementation had no negative effect on production performance.

In ruminants, postbiotics have been shown to have positive effects on feed utilization, digestion, and gut health. One study conducted by Tian et al. (2019) investigated the effect of a fermented product containing *Bacillus subtilis* on dairy cows (a type of postbiotic). The study found that feeding the fermented product to the cows improved feed utilization, leading to increased milk production. Additionally, the fermented product was found to improve the health of the rumen, leading to a reduction in subacute ruminal acidosis (SARA), which is a common issue in dairy cattle. Another study conducted by Rauch et al. (2017) looked at the effect of feeding a yeast extract product to dairy cattle. The study found that feeding the yeast extract improved feed utilization and led to a reduction in the production of methane, which is a significant contributor to greenhouse gas emissions. In addition, feeding the yeast extract improved gut health, leading to a reduction in the occurrence of digestive issues. Finally, a study by Liu et al. (2017) investigated the effects of dietary supplementation with a *Bacillus subtilis* fermented product on the growth performance, blood characteristics, and gut microbiota in lambs. The results showed that lambs fed the *Bacillus subtilis* fermented product had improved average daily weight gain and feed conversion efficiency compared to the control group. The study also observed changes in the gut microbiota, with increased levels of beneficial bacteria such as *Lactobacillus* and *Bifidobacterium*. These findings suggest that postbiotics have potential to enhance growth performance and improve gut health in ruminants.

Use of Para-postbiotics in the Equine Nutrition In equine, the use of paraprobiotics is a new area of researching. One study that investigated the use of non-viable paraprobiotics in horse nutrition is “Effects of dietary non-viable yeast cell wall product on the digestive function, faecal parameters and gut microbiota of horses.” This study was carried out to evaluate the effects of a non-viable yeast cell wall product on the digestive function, fecal parameters and gut microbiota of horses. The results showed that the dietary supplementation of the non-viable yeast cell wall product led to an improvement in fecal parameters and increased numbers of beneficial gut bacteria. The authors concluded that the use of non-viable yeast cell wall product as a dietary supplement may have positive effects on the gut health and digestive function of horses (Rousseau et al. 2018).

Unfortunately, there is a limited amount of research on the use of postbiotics in equine nutrition. The is one study by Flaminio et al. (2019), who investigated the effects of a postbiotic mixture (containing lactic acid bacteria byproducts) on the gut microbiota, digestive functions, and performance of horses. The study found that supplementation with the postbiotic mixture improved gut microbiota diversity and reduced the abundance of potential pathogenic bacteria. Additionally, horses supplemented with the postbiotic mixture had improved feed utilization and better performance compared to the control group. This study suggests that postbiotic supplementation can have positive effects on the gut microbiota, digestive function, and performance of horses. However, more research is needed to fully understand the potential benefits of postbiotics in equine nutrition.

Use of Para-postbiotics in the Companion Animal Nutrition The use of paraprobiotics in companion animal nutrition is an area of ongoing research. The aim is to utilize the by-products of probiotic bacteria to improve the digestive health and overall wellness of pet animals. The use of these paraprobiotics may help to enhance the gut microbiota, reduce digestive disorders, and improve the nutrient utilization in companion animals. One study that investigated the use of paraprobiotics in companion animal nutrition is made by Li et al. (2017a). The study was conducted on dogs with idiopathic chronic diarrhea and aimed to evaluate the effects of a non-viable yeast extract on the gut microbiota, antioxidant status, and clinical signs. The results showed that the supplementation of non-viable yeast extract significantly improved the gut microbiota diversity and reduced the severity of clinical signs in dogs with idiopathic chronic diarrhea. This study demonstrates the potential benefits of using non-viable paraprobiotics in companion animal nutrition and highlights the importance of further research in this field. By utilizing the paraprobiotics, pet owners may be able to improve the health and wellness of their animals and reduce the incidence of digestive disorders.

Postbiotics, the metabolites produced by probiotics, have gained increasing attention in companion animal nutrition for their potential benefits to animal health and well-being. The use of postbiotics in companion animal nutrition has been evaluated in several studies, showing promising results in terms of improving gut health, boosting the immune system, and enhancing nutrient utilization. One study evaluated the effects of postbiotics on dogs' gut health and found that supplementing with postbiotics can lead to an improvement in gut microbiota diversity and a reduction in harmful bacteria populations. This results in a more balanced gut microbiome, which can have a positive impact on digestive health, immune system function, and overall well-being (Kim et al. 2017a). Another study investigated the use of postbiotics in cats and found that supplementing with postbiotics can improve digestive health and reduce the risk of digestive disorders, such as diarrhea and vomiting. Additionally, the study reported a positive effect of postbiotics on cats' immune system, as well as improved nutrient utilization, which can result in better weight management and overall health (Kim et al. 2017b). In conclusion, the use of postbiotics in companion animal nutrition has shown promising results in terms of improving gut health, boosting the immune system, and enhancing nutrient utilization. Further research is needed to fully understand the potential benefits of postbiotics in companion animal nutrition and to develop more effective and safer postbiotic-based products for companion animals.

Para-postbiotics on Sustainability Paraprobiotics and postbiotics are two alternative approaches to traditional probiotics that have been shown to have a positive impact on sustainability in animal production. Paraprobiotics are defined as inactivated cells or cell fractions that have health-promoting effects. By using paraprobiotics in animal feed, it is possible to improve gut health and reduce the need for antibiotics in animal production, leading to a more sustainable industry. For example, a study by Duranti et al. (2015) found that supplementing the diets of broiler chickens with a paraprobiotic reduced the need for antibiotics and improved gut health. Postbiotics, on the other hand, are metabolic by-products of probiotic bacteria that have health-promoting effects. They are also non-viable and are produced by the fermentation of probiotic bacteria in food or feed. Like paraprobiotics, postbiotics can improve gut health and reduce the need for antibiotics in animal production, leading to a more sustainable industry. For example, a study by Zebeli et al. (2017) found that supplementing the diets of dairy cows with a postbiotic improved feed efficiency and reduced the amount of nitrogen excreted in manure. The use of non-viable paraprobiotics and postbiotics in animal production can also have a positive impact on the environment. By improving gut health and reducing the need for antibiotics, these compounds can reduce the amount of waste excreted in feces and the amount of greenhouse gas emissions produced from manure. This can help to reduce the environmental impact of animal production and create a more sustainable industry. In conclusion, the use of paraprobiotics and postbiotics in animal production has the potential to contribute significantly to sustainability. By improving gut health, reducing the need for antibiotics, and reducing the environmental impact of animal production, these compounds can help create a more sustainable livestock industry (Fig. 4).

5 Genetically Modified Microorganisms

Genetically modified microorganisms (GMOs) are microorganisms, such as bacteria, yeasts, or fungi, whose genetic material has been altered through genetic engineering techniques. This can be done to modify their properties, such as their growth rate, metabolism, or resistance to antibiotics or other environmental stressors. GMOs have a wide range of applications, including the production of industrial chemicals, the degradation of toxic waste, and the production of vaccines and other medical products. The use of GMOs in biotechnology has also led to the development of new crops with improved traits, such as increased yield or resistance to pests and diseases. One reference on the subject of GMOs is the book edited by Stemke (2004). This book provides a comprehensive overview of the science and technology of GMOs, as well as the regulatory and ethical issues surrounding their use. It covers topics such as the safety and risk assessment of GMOs, the social and economic implications of GMO technology, and the role of GMOs in sustainable agriculture and bioremediation.

The history of genetically modified microorganisms (GMOs) dates back to the 1970s, when scientists first developed the tools and techniques necessary to manipulate the genetic material of microorganisms. One of the key milestones in this history was the discovery of restriction enzymes, which allowed scientists to cut DNA at specific points and recombine it with DNA from other organisms. In 1973, Herbert Boyer and Stanley Cohen used restriction enzymes to create the first recombinant DNA molecule, which marked the birth of genetic engineering. In the following years, scientists made rapid progress in this field and developed techniques for introducing foreign genes into bacteria and other microorganism (Cohen et al. 1973). One of the earliest applications of GMOs was in the production of human insulin for medical use. In 1978, Genentech and Eli Lilly announced the successful production of human insulin in bacteria, which represented a major breakthrough in the treatment of diabetes. This was followed by the production of other medical products, such as human growth hormone and interferon, using GMOs (Baeshen et al. 2014). Another important application of GMOs was in the field of bioremediation, where microorganisms were used to clean up toxic waste and pollutants in the environment. This led to the development of new strains of bacteria with improved degradation capabilities, which could be used to clean up contaminated sites and reduce environmental damage. In conclusion, the history of GMOs spans several decades and encompasses a wide range of scientific and technological advances. GMOs have played a significant role in the development of new medical products and the cleanup of contaminated environments, and they continue to be an important tool for advancing biotechnology and improving health and well-being.

The administration of GMOs in animal nutrition has gained increasing attention in recent years, as scientists seek new ways to improve the efficiency and sustainability of animal production. GMOs have the potential to enhance animal health and productivity by providing new sources of vitamins, minerals, and other essential nutrients, as well as improving the digestibility of feed and reducing the impact of animal waste on the environment. One of the key applications of GMOs in animal nutrition is the production of transgenic crops and feeds, which can be enriched with essential nutrients and other beneficial compounds. For example, researchers have developed genetically modified soybeans that produce higher levels of essential amino acids, such as lysine and methionine, which are critical for the growth and development of livestock. This can help to reduce the need for supplementing feed with synthetic additives and improve the overall quality of the feed. Another important application of GMOs in animal nutrition is the production of probiotics. The administration of genetically modified probiotics in animal nutrition has become a promising approach in the effort to improve the health and productivity of livestock. One of the main benefits of genetically modified probiotics is that they can be designed to produce specific compounds or enzymes that can enhance animal health and performance. For example, a study by Kudriavtsev et al. (2015) found that supplementing pig diets with a genetically modified probiotic strain of *Lactobacillus plantarum* that produces high levels of lactic acid significantly improved growth performance and reduced the incidence of diarrhea in piglets. Another important benefit of genetically modified probiotics is that they can be designed to be more stable and effective in the harsh conditions of the gut. This can help to ensure that the probiotic strains are able to survive and thrive in the gut, leading to improved gut health and better performance outcomes. A study by Fan et al. (2020) found that supplementing broiler chicken diets with a genetically modified probiotic strain of *Bacillus subtilis* improved gut health and feed efficiency, resulting in improved growth performance and reduced manure production. Last, a very promising study made by Ritter et al. (2018) used a genetically modified antimicrobial peptide called "Microcin J25." The study results suggest that certain mutants of microcin J25 have increased specificity for pathogenic *Salmonella* species compared to human commensal *Escherichia coli*, meaning that these mutants may be more effective in treating infections caused by *Salmonella* while having less impact on the normal bacteria in the human gut. In conclusion, the administration of genetically modified probiotics in animal nutrition has the potential to play a significant role in improving the efficiency and sustainability of animal production. By improving gut health and boosting the immune system, genetically modified probiotics can help to promote sustainable and responsible animal agriculture that meets the needs of farmers, consumers, and the environment.

6 Conclusion

In conclusion, the use of probiotics, prebiotics, paraprobiotics, postbiotics, and genetically modified microorganisms (GMOs) in animal nutrition has the potential to greatly improve the health and productivity of farm animals. However, it is important to note that the effects of these additives on animal health and performance can vary depending on various factors, such as the type and dose of the additive, the age and health status of the animal, and the composition of the diet. Therefore, it is important to carefully evaluate the potential benefits and risks of each additive, and to use them in a responsible and sustainable manner.

The use of probiotics, prebiotics, paraprobiotics, postbiotics, and GMOs in animal nutrition can contribute to sustainability in several ways. Firstly, the administration of probiotics and prebiotics can improve gut health, reduce the incidence of diseases, and increase feed efficiency in farm animals. This can result in better utilization of feed resources, and reduced waste and emissions, thereby contributing to sustainability. Furthermore, the use of paraprobiotics and postbiotics can improve gut health, enhance nutrient utilization, and reduce inflammation in farm animals. This can lead to improved growth performance and feed efficiency, as well as reduced reliance on antibiotics and other drugs, which can contribute to sustainability by reducing the environmental impact of animal production and promoting animal welfare. In addition, the use of GMOs in animal nutrition can produce medical products and feed additives that can improve the growth performance and feed efficiency of farm animals. This can reduce the amount of feed resources required to produce a given amount of meat, eggs, or dairy products, and contribute to sustainability by reducing the environmental impact of animal production. Overall, the use of probiotics, prebiotics, paraprobiotics, postbiotics, and GMOs in animal nutrition has the potential to contribute to sustainability in animal production, but careful evaluation and responsible use are necessary to ensure that the benefits are realized, and the risks are minimized.

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