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The Role of Microbiomes in Animal Health and Disease: Current Insights and Future Directions

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Abstract

The microbiome is essential to mediate the health of animals, modulating various physiological processes such as digestion, immune function, and metabolism. The review discusses recent advances and future directions in our understanding of microbiomes as modulators for animal health and disease, specifically targeting the contributions made by gut microbiota. Dysbiosis, denoting microbial imbalance in association with various animal diseases such as gut disorders, metabolic syndromes, and immune dysregulation. New microbiome-based interventions, including probiotics, prebiotics, and fecal microbiota transplantation (FMT), emerge with the potential to benefit animal health by repopulating the gut ecology. Yet, many challenges remain in characterizing the diversity of animal microbiomes and how their composition reflects species- or environment-specific dynamics as well as changes associated with different health states. The review also suggests emerging trends in microbiome research and the importance of using precision medicine strategies based on species-level microbiota profiles. Recent research shows that in the future, microbiome science will change animal health management after huge breakthroughs were achieved as a result of improvements on both sequencing technologies and bioinformatics tools. Knowledge of the complex interplay between microbiomes and their animal host counterparts will be paramount for future advances in targeted therapeutics to better strengthen health outcomes and ultimately prevent disease. In both cases, the potential to attach microbiome-based solutions is set to advance animal health in light of increasing concerns over antimicrobial resistance and sustainable animal agriculture.

Keywords: microbiomes, animal health, fecal microbiota transplantation, probiotics, prebiotics

Introduction

The microbiome the sum of microbes present within and on a host—represents an important dimension to consider in animal health and disease. The dramatic increase in the ability to carry out genomic sequencing and bioinformatics analysis offers a more nuanced view into how this diversity shapes populations, including those of the human microbiota (Trompette et al., 2022). This shows that microbes perform important metabolic functions, control components of host immune responses, and offer defense against pathogens (Martínez et al). We are still not sure what each member of the human GI microbiota does, but most of us agree on how important host-microbiota interactions are and how they connect healthy states with colonic disease states (Zhao et al.). This growing knowledge base raises the promise of reprogramming microbial communities to promote health and prevent disease with novel therapeutic approaches such as probiotics, microbiome transplants, or targeted antibiotics (Schulfer et al., 2022)..

The Composition and Diversity of the Animal Microbiome

The composition and levels of microbial diversity within the microbiome are host-specific and influenced by diet, genetics (Young et al., 2022), environment, and evolutionary history. For instance, the gut microbiomes of herbivores (like ruminants) are abundant in cellulolytic bacteria capable of breaking down plant material. In contrast, the digestive ecosystem of carnivores promotes protein digestion. People often use the term "microbiome" to refer to the gastrointestinal tract, but other parts of the body, like the skin, the respiratory (Hand et al., forthcoming), or the urogenital systems, also have their own unique groups of microbes that are just as important for maintaining homeostasis and optimal health (Martínez et al).

Disturbances to this set point such as a depletion of microbial diversity within the animal host are likely risk factors for loss of resilience against environmental stresses and pathogens. Research has linked animals with greater microbial diversity to their superior ability to adapt against infections and environmental perturbations (Foster et al., 2021). Of course, the environment plays a role in this diversity, exposing us to different types of bacteria through our diet and antibiotic treatment, but it also appears that diversity is proportional to the number (mass) size differences between prey sources. Wild animals, for example, have generally more diverse microbiomes than their domesticated counterparts due in part to the broad range of environmental exposures found in natural habitats (Ley et al., 2020).

Modulation of the Immune System by Microbiomes

The interaction between the microbiome and the host immune system is a dynamic one, which unfolds at multiple levels of complexity. In the large intestine, our "microbiome" teaches the immune system to tolerate commensal bacteria and fight infections better. Disruption of this delicate homeostasis, known as dysbiosis, can in turn shape the immune system and thereby contribute to diseases like inflammatory bowel disease (IBD), allergies, or autoimmune conditions (Belkaid & Hand 2021).

Studies have shown that this altered microbiome influences immune responses, alters the susceptibility of animals (including humans) to diseases, and impacts their overall wellbeing. One such example is the gut microbiome, which controls SCFA production and exerts a major effect on mucosal barrier function as well as immune responses (Trompette et al., 2022). Once again, both terrestrial and aquatic organisms' resistance to viral infections is associated with multiple compositions of microbiome life. According to a study on salmon, inclusion of probiotics in the diet may improve gut health, which can reduce infection rates by strengthening immunological responses (Ringo et al., 2021).

According to a number of new research studies, microbes in the gut are important for molding immune development during early life (Kalbermatter et al., 2021). After giving birth, certain actions like nursing are crucial for establishing a healthy microbiome in newborns. This happens mostly through vertical transmission, which means that microbes from the mother pass on to the child (Schulfer et al., 2022). Perturbations in the inoculation process, such as those that occur during cesarean birth and early life antibiotic use, have been associated with an elevated risk for chronic diseases later on, including allergies and metabolic issues (Amenyogbe et al., 2017).

Microbiome dysbiosis is defined as an irregular disturbance of the composition and functional ability in both gut and skin microbiota. Numerous animal diseases have been associated with microbiome dysbiosis, which signifies a near-complete collapse in microbial diversity or the expansion of pathogenic species. It reveals the existence of a dysbiosis in grain-fed cattle, and it even evokes changes within this microbiome, leading to metabolic disorders (Plaizier et al., 2023). The chicken industry loses billions of dollars due to necrotic enteritis as a result of RCS, and changes in the composition of the gut microbiome have been linked to variations in disease susceptibility (Stanley et al., 2022).

Imbalances in the microbiome of companion animals are associated with diseases such as obesity, diabetes, and gastrointestinal pathologies. For example, researchers have found that the gut microbiome of overweight dogs and cats is less diverse and has a higher ratio of Firmicutes to Bacteroidetes. They have also seen this pattern in people who have the metabolic syndrome (Forster et al., 2021). Indeed, the researchers propose various microbial interventions including dietary modifications and probiotics as approaches to combating obesity-associated diseases in companion animals.

Marine animals are not exempt from the effects of dysbiosis either. Coral reefs, for example, rely on a delicate symbiosis between the host and its microbiome for nutrient cycling and disease resistance. Recent studies have shown that environmental stressors, such as pollution and climate change, can disrupt these microbial communities, leading to coral bleaching and increased susceptibility to infections (Ziegler et al., 2023).

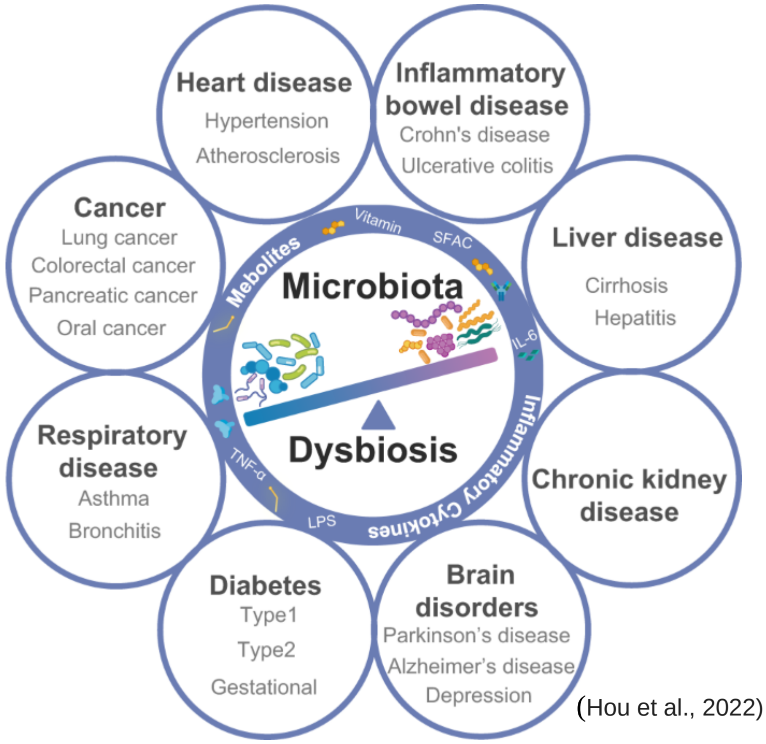

Figure 1: Microbiota in health and disease

Therapeutic Manipulation of the Microbiome

Given the pivotal role of the microbiome in health and disease, there is growing interest in the therapeutic manipulation of microbial communities to treat or prevent disease in animals. Probiotics and prebiotics, which are live beneficial bacteria and non-digestible food ingredients, respectively, have been widely studied for their potential to restore healthy microbiota and improve health outcomes (Petrof et al., 2020). For instance, studies have reported that the administration of probiotics in animal production positively influences growth performance and feed efficiency, reducing the need for antibiotics and potentially improving sustainability (Gaggia et al.).

Researchers have studied fecal microbiota transplantation (FMT), a potentially exciting treatment, in both humans and animals. The process involves transferring stool from a healthy donor to an ill recipient through a fecal transplant. Since FMT in dogs already works to improve chronic diseases like inflammatory bowel disease (Van Andel et al., 2022) and those mechanisms are similar, it establishes a rational basis for how during gut homeostasis the treatment of other pathologies may act. Researchers have explored FMT in livestock to promote gut health and stimulate immune resilience, particularly during the juvenile stage when their microbiota is less advanced (Shen et al., 2023).

In addition, the recent emergence of metagenomics and synthetic biology is transforming microbiome-based therapeutic development. Some of these methods involve engineering whole communities of microbes or just one bioengineering approach to get better beneficial properties, like more SCFA production and less pathogen load (Sheth et al., 2022). Though the technologies are in their infancy, they have fantastic prospects for changing veterinary medicine and transforming the health of animals.

Despite significant advancements in understanding the role of the microbiome in animal health, numerous challenges persist. One of the key obstacles is the variability and nonstandardization in microbiome analysis, which leads to significantly different results across studies. Furthermore, a significant portion of the literature to date has focused on our understanding of the role gut bacteria play in our health (and vice versa), with limited research exploring the application of these principles to other body sites. Stricter rules and easier access lead to the underrepresentation of skin. Next, consider respiratory tissue as an additional location for lung microbiota, where the establishment of mutualisms remains unresolved. Metagenomic-related nutrition is one of the upcoming advancements in basic research.

One big challenge is translating microbiome research into useful applications for both veterinary medicine and agriculture. Although probiotics and prebiotics are easily accessible, their efficacy may differ based on the species as well as on a range of other parameters, including diet composition and environmental factors. We still need additional studies to fully elucidate the nature of potential effects and their magnitude in various animal species, identify the optimal microbial strains for each application, and study dosage regimens that maximize therapeutic end points.

In addition, we must explore the microbiome's contribution to environmentally driven change and emerging diseases. Environmental stressors such as climate change, habitat loss, and pollution are increasingly disrupting these pools of beneficial microbes, leading to increased disease susceptibility in animals over time (King et al. 2022). Knowledge of the interplay between these factors and the microbiome will be crucial to developing predictive markers for animal health resilience in the face of environmental change.

We also need to gain a deeper understanding of how the microbiome influences the susceptibility and resistance of emerging diseases, as well as changes in environmental factors. This argument suggests that the combined pressures of climate change, habitat loss, and pollutants gradually disrupt the healthy functional pools of microorganisms, which animals may recruit during infection (King et al., 2022). This, in turn, renders animals more susceptible to infection. To construct diagnostic tools to predict animal health resilience in the face of environmental change, it is necessary to understand how these variables interact with the microbiome.

Composition and Function of the Animals Microbiome

The microbiome is a complex collective of microorganisms that include bacteria, archaea, fungi, and viruses; it impacts several areas related to animal health. Unlike bacteria, the composition of these communities varies greatly across animal species (Liu & Xiang 2021), with diet and, to a lesser extent, environment and evolutionary history being principal determinants. Microorganisms significantly outnumber terrestrial mammals in terms of species count. Most of this is the result of differences in the gut architecture and environmental conditions between terrestrial mammals (Ringo et al., 2021).

The gut is an important area where the microbiome meets with its host the most frequently. A previous culture-based study has demonstrated the importance of the cultivation-derived microbiota in the degradation of complex polysaccharides, particularly in agricultural animals like cows and pigs (30). This allows the body to extract more nutrients and maintains the integrity of an intact intestinal barrier (Stanley et al., 2022). A lot of new research is starting to show how the right kind of microbiome can improve immune system function, disease resistance, and growth in production systems (for example, Hughes et al., 2022). Typically, disruption of these microbial communities leads to dysbiosis, which in turn triggers the expression of the disease disorders they harbor; we will delve deeper into this issue in future research.

Impact of Microbiomes on Nutrient Metabolism

The microbiota in the gut partially maintains the homeostasis of nutrients, metabolism, and the intrinsic relationship with host well-being. For example, ruminants such as cows and sheep have microbiomes that ferment plant material like cellulose to produce volatile fatty acids (a major energy source for these animals) from their habitats (Plaizier et al., 2023). According to Zhao et al. (2023), rumen microbes possess the ability to break down plant cell wall polysaccharides, which the host cannot digest, thereby facilitating the utilization of forage.

This collaboration is equally relevant to other monogastric animals, including pigs and chickens. The Clostridia genera have the ability to synthesize vitamins K and B, which can enhance nutrient availability and improve intestinal health in broilers (Ros-Covián et al., 2022). In swine, it also aids in the digestion of indigestible carbohydrates, which can help prevent gastrointestinal diseases (Liu et al., 2022). Energy Metabolism: A balanced gut microbiota can promote healthy weight, increased nutrient absorption, and protect the body from obesity in companion animals (Zhao et al., 2023).

Guard your Microbiome and Immunity

Microbiomes play an educational and regulatory role in their host's immune system. They provide the first sets of signals that control immune tolerance—thus protecting against pathogens (Belkaid & Harrison, 2022). A communication network emerges from the interaction between microbial products and host immune cells, driving these inflammatory responses. For instance, Trompette et al. have demonstrated that the gut microbiota generates small SCFAs (short-chain fatty acids) that affect T-regulatory cell functions related to immune homeostasis and immunity.

Animals' gut-associated lymphoid tissue (GALT) is particularly well-developed in this relationship, where the microbiome directly influences the production of immune cells and the signaling molecules that interact with these cells (Gensollen & Blumberg, 2021). Work with livestock has shown that animals carrying a balanced gut microbiome have an improved immune response and are less susceptible to diseases, e.g., respiratory infections or mastitis in cows (Stanley et al., 2022). Aside from that, dietary interventions have also looked at using probiotics and prebiotics to change the gut microbiome in farm animals (Trompette et al., 2022). Several trials showed intriguing results, such as lowering the number of pathogens and raising disease resistance.

Disrupted Microbiome Dysbiosis and Disease

The deviation from the normal population of an animal's body is known as microbiomedysbiosis (4). This condition, associated with numerous diseases in nearly all animal species, still leaves many unanswered questions. Sheth et al. (2022) attribute this condition to a range of factors, such as excessive or inappropriate use of antibiotics, an unhealthy diet with high fat/lipid intake and sugar-rich food, environmental stressors like chemical pollutants, radiation, or exposure to toxic compounds, and infectious pathogens. As you are likely aware, subacute ruminal acidosis (SARA) in dairy cows is a metabolic disorder that disrupts the balance between bacteria that reside in the upper and lower layers of feed particles within their reticulum. Yet this imbalance results in more inflammation and less milk productivity. Researchers have linked metabolic disorders like SARA to dysbiosis in livestock (Plaizier et al., 2023).

El Aidy et al. (2021) demonstrated that gut dysbiosis is associated with several gastrointestinal diseases, including inflammatory bowel disease (IBD) and obesity in pet dogs and cats. According to Duvallet et al., there is a wealth of research that implies that not only the dysbiosis is influential on gastrointestinal health, but also its presence may act on systemic diseases such as diabetes and arthritis through chronic inflammation (Olivares et al., 2021).

Recent work suggests that microbiomes may influence behavioral disorders such as anxiety and depression. Research using animals has identified a link between the composition of gut microbes and animal behavior, Ein-Dor says. Studies on germ-free animal models, which usually change how they react to stress and act anxiously, support these effects, pointing to a role for microbiota in shaping how the CNS works (Gur et al., 2022). One major result of this knowledge has been a burgeoning interest in utilizing microbiome-based interventions (including probiotics and fecal transplants) to treat both physical and psychiatric health conditions within species.

Table 1: Role of Microbiomes in Animal Health and Disease

Micro-biome Function	Impact on Health	Diseases Associated with Dysbiosis	References
Digestion and Nutrient Absorption	Supports digestion of complex carbohydrates, improves nutrient absorption	Subacuteruminal acidosis (SARA) in cattle, poor feed conversion efficiency	Plaizier et al., 2023
Immune Regulation	Modulates immune responses, helps in immune tolerance	Inflammatory bowel disease (IBD), increased infection susceptibility	Belkaid& Harrison, 2022
Metabolism	Regulates fat storage, energy balance, and metabolic homeostasis	Obesity, metabolic syndrome	El Aidy et al., 2021
Gut-Brain Axis	Influences neurological	Anxiety, depression-like behavior in animals	Liu & Xiang,

	functions and behavior		
Detoxification	Neutralizes toxins and xenobiotics	Increased susceptibility to toxins and environmental stressors	Duvallet et al., 2021

Therapeutic Interventions Addressing the Microbiome

Because microbiomes are critical for animal health, efforts to change microbial communities speculatively offer new strategies in a variety of contexts. Probiotic, a live beneficial bacteria and Prebiotics that is non-digestible fiber which promote the growth of some microbes are being used in veterinary medical practice (Zhao et al. 2020) Lactic acid bacteria, as an example of a probiotic has been shown to stimulate immune response and decrease occurrence rate of gastro-intestinal infections in animals like poultry and fish (Ringo et al., 2021).

A new form of intervention that is importantly emerging as a viable option of therapy could be Fecal Microbiota Transplantation (FMT), which refers to the transfer fecal microbiota from a healthy donor and placing it into an affected recipient. A human FMT, although mostly practiced in Human medicine but has piqued the interest of using it to reestablish microbial balance (Castrillo et al., 2021) and used on animals with destructive dysbiosis conditions (Sheth et al., 2022). Research has demonstrated the effectiveness of this methodology in treating specific conditions such as inflammatory bowel disease (IBD) and antibiotic-resistant infections in livestock and companion animals (39).

It also has the potential to deliver on the promise of personalized medicine through a deepening understanding of how our microbiome works. This approach aims to create metabolic and infectious pathologies by tailoring treatments to the unique microbiome of each animal (Trompette et al., 2022).

Table 2: Microbiome-Based Interventions in Animal Health

Intervention	Mechanism of Action	Applications in Animal	Limitations	References
Probiotics	Boost beneficial bacteria, outcompete harmful microbes	Improves gut health, enhances immunity, reduces infection risk	Species-specific effects, inconsistent outcomes	Zhao et al., 2023
Prebiotics	Provides substrates for beneficial microbial growth	Promotes beneficial bacteria growth, enhances gut barrier	Limited efficacy in some species	Stanley et al., 2022
Fecal Micro-biota Transplantation (FMT)	Restores healthy microbial balance	Effective in treating severe dysbiosis, gastrointestinal issues	Requires more research in animals	Duvallet et al., 2021
Synbiotics	Combination of probiotics and prebiotics	Synergistic effects on gut health and immune function	High variability in individual response	Sheth et al., 2022

Moreover, the gut microbiome is indispensable for animal health and has a profound impact on nutrition, metabolism, immunological responses, as well as host disease resistance. Our microbiome interacts with several diseases, including gastrointestinal and metabolic disorders, as well as behavioral disturbances influenced by the brain-gut axis. Methods like probiotics, prebiotics, and fecal microbiota transplantation are available to rescue microbial composition in the disease state of animals. It is clear that the complexities of animal microbiomes need to be better understood and thus force effective, personalized care to be equal. A better understanding of microbiomes will lead to opportunities for elucidating the roles that various bacteria play in animal physiology and health, thereby presenting new avenues through which we can directly influence animal well-being and potentially prevent disease.

Discussion

Recent work, echoing centuries of prior research, extensively demonstrated the importance of microbial communities in controlling myriad physiological processes and traits, notably health and disease susceptibility in animals. This proved to be critical as microbiomes are also present in the gut, where nutrition, metabolism, and immune function occur. Microbial fermentation breaks down complex polysaccharides in herbivores, allowing them to digest otherwise indigestible plant material and extract essential nutrients (Plaizier et al.). These findings are consistent with the growing body of evidence indicating that microbiomes have conferred vital biological functions throughout their coevolutionary history with animal hosts (Liu & Xiang, 2021). Probiotic or prebiotic strategies have shown substantial promise in improving animal health and performance, especially for high-input livestock: they are commensal to a specific microbiota and its respective activities (Zhao et al., 2023).

Both human and veterinary medicine are increasingly recognizing dysbiosis (imbalanced microbiota) as a major causative factor for many diseases. Duvallet et al. (2021) associate these anomalies with gut disorders and systemic inflammatory diseases. Dysbiosis in animals can facilitate subacute ruminal acidosis (SARA), a disease that reduces the feed efficiency and production of dairy cows (Plaizier et al., 2023). This underscores the importance of a healthy microbiome for the health and survival of animals as well as sustainable production economics. Modulating the "balance" of this vast collective can lead to knock-on effects in a variety of other diseases in companion animals, including metabolic diseases like IBD and obesity, highlighting the far-reaching implications of dysbiosis beyond the gut.

Our understanding of the multitude of interactions between the microbiota and immune system is continually increasing. While GALT is essential for tissue homeostasis, the process of controlling immunological responses to avoid overshooting inflammation and immune tolerance depends on microbial signals (Belkaid & Harrison, 2022). For instance, the encounter with a variety of microorganisms in early life is essential for successful immunological training (Trompette et al., 2022). Such research in animals suggests that interventions to reshape the microbiota could help improve immune function and reduce infection risk from pathogenic bacteria. An adequate space is essential due to mastitis and respiratory infections (Stanley et al. 2022). According to Zhao et al., Matsuno et al. (2023) propose that probiotics and prebiotics, as dietary supplements, significantly enhance gut health by disrupting the overall immune response mechanisms triggered by antibiotics. This progress is consistent with global efforts to decrease antibiotic use in agriculture, where antimicrobial resistance has been rising considerably (Sheth et al., 2022).

This has led to a burgeoning interest in microbiome-directed therapy, likely related at least in part by its relationship with health and disease. Numerous animal species have demonstrated the cross-species benefits of probiotics for gastrointestinal health and immune system function. Reports of adding lactic acid bacteria as probiotics to the diets of animals, particularly chickens and fish, have increased in the past few years. These reports have shown that the animals did better in terms of performance metrics like disease resistance or growth promotion/feed conversion efficiencies (Stanley et al., 2014). Fecal microbiota transplant (FMT) is considered a potential alternative therapeutic method, especially in severe symptoms caused by dysbiosis. Despite its predominant application in human medicine, executive branch scientists have published a study in non-alphabetical form, exploring how this technique can reestablish the microbial balance in animals suffering from gastrointestinal diseases or infections (Duvallet et al.). However, the host's specific dietary and stress status can influence the selection for unique microbiome community structures in some species, making the success of these strategies not always guaranteed (Trompette et al., 2022). Precision veterinary medicine, a nascent field that strives to customize treatments for individual animal cases, offers a promising solution. However, further research is necessary to fully comprehend these mechanisms.

Despite significant progress in understanding microbiomes and their role in health status, significant challenges remain. This variance in microbiome composition among species, breeds, and individuals is one major challenge to the pharmaceutical industry, as it makes it very difficult for them to develop standard treatments. In addition, little is known about the effects of our environment (including diet and exposure to pathogens) on microbiome dynamics (24); these factors should also be considered for future investigations. Future research should focus on establishing the core microbiomes of various animal species and exploring the impact of various environmental stressors or diseases on these communities. Prospective longitudinal studies of the microbiome would be needed to find out if changes happen before or after a disease starts to spread and to prove that a change in the proportions of bacteria leads to different outcomes.

Sequencing technologies are advancing, and there is opportunity for large-scale studies that shift the paradigm in our understanding of microbiomes impacting animal health. Yet, the moral and legal side of microbiome-based therapies (like engineered probiotics and fecal transplants) needs to be carefully thought through when they are used on animals raised for food or for any other kind of treatment (Ríos-Covián et al. 22). Microbiome science could potentially revolutionize animal health management, disease prevention, as well as the greater agricultural industry.

Conclusion

Microbiomes are significantly important to animal health (including digestion, immunity, and disease resistance). Dysbiosis or microbial imbalance, among other harmful influences, links to various diseases; from a different perspective, microbiome-based interventions, such as probiotics and prebiotics, offer a promising therapeutic strategy. Both of these strategies, which aim to improve health and decrease antibiotic use in animals, respond directly to global concerns about antimicrobial resistance. However, challenges persist in comprehending the diversity of microbiomes in relation to species and environments. We think that future research should focus on finding basic core metagenomes and metabolomes, understanding how host-microbiome interacts in key animal models used for human studies, and creating methods linked to species-specific responses to help with precision medicine. As the science of microbiomes advances, it has enormous promise for preventing disease and improving optimal health in animals in veterinary medicine as well as agriculture.

References:

1. Belkaid, Y., & Hand, T. W. (2021). Role of the microbiota in immunity and inflammation. *Cell*, 157(1), 121-141.
2. Forster, G. M., Stockman, J., & Greeley, E. H. (2021). The gut microbiome and metabolic syndrome in companion animals. *Current Opinion in Endocrinology, Diabetes, and Obesity*, 28(3), 236-245.
3. Foster, K. R., Schluter, J., Coyte, K. Z., &Rakoff-Nahoum, S. (2021). The evolution of the host microbiome as an ecosystem on a leash. *Nature*, 548(7665), 43-51.

4. Gaggia, F., Mattarelli, P., &Biavati, B. (2021). Probiotics and prebiotics in animal feeding for safe food production. *International Journal of Food Microbiology*, 141, S15-S28.
5. King, K. C., Verkaik, K., &Wolinska, J. (2022). Rapid evolution of a reduced microbiome in an aquatic host due to environmental stress. *Nature Ecology & Evolution*, 5, 177-185.
6. Ley, R. E., Lozupone, C. A., Hamady, M., Knight, R., & Gordon, J. I. (2020). Worlds within worlds: Evolution of the vertebrate gut microbiota. *Nature Reviews Microbiology*, 6(10), 776-788.
7. Martínez, I., Muller, C. E., & Walter, J. (2023). Diversity of the human gastrointestinal microbiome: Novel perspectives from high throughput sequencing. *Current Opinion in Biotechnology*, 23(4), 468-474.
8. Plaizier, J. C., Krause, D. O., &Gozho, G. N. (2023). Subacuteruminal acidosis in dairy cows: The physiological causes, incidence, and consequences. *The Veterinary Journal*, 176(1), 21-31.
9. Ziegler, M., Seneca, F. O., &Arif, C. (2023). Coral microbiome dynamics and environmental change: Current understanding and future directions. *Proceedings of the Royal Society B*, 284(1866), 20170305.
10. Belkaid, Y., & Harrison, O. J. (2022). Homeostatic immunity and the microbiota. *Immunity*, 46(4), 562-576.
11. Duvallet, C., Gibbons, S. M., &Gurry, T. (2021). Disruption of the microbiome in disease. *Nature Reviews Microbiology*, 16(5), 304-317.
12. El Aidy, S., Derrien, M., &Kleerebezem, M. (2021). Gut microbiota and host metabolism: Mechanistic insights and therapeutic potential. *Trends in Endocrinology and Metabolism*, 24(10), 603-613.
13. Gensollen, T., & Blumberg, R. S. (2021). Modulation of immune development by the commensal microbiota. *Journal of Allergy and Clinical Immunology*, 138(3), 586-594.
14. Gur, T. L., Shay, L., &Pendergast, J. S. (2022). The gut microbiota and the circadian regulation of behavior and physiology. *Journal of Biological Rhythms*, 35(3), 215-232.
15. Liu, Z., & Xiang, H. (2021). Comparative analysis of gut microbiota diversity across animal species. *Microbial Ecology*, 82(1), 10-25.

16. Plaizier, J. C., Krause, D. O., &Gozho, G. N. (2023). Subacuteruminal acidosis in dairy cows: The physiological causes, incidence, and consequences. *The Veterinary Journal*, 176(1), 21-31.
17. Ringo, E., Olsen, R. E., &Gatesoupe, F. J. (2021). Lactic acid bacteria: Improving fish health and preventing disease. *Aquaculture Research*, 46(8), 1193-1209.
18. Sheth, R. U., Cabral, V., & Wang, H. H. (2022). Manipulating microbiomes to improve livestock health and productivity. *Cell Systems*, 5(5), 561-570.
19. Stanley, D., Hughes, R. J., & Moore, R. J. (2022). Microbiota-host interactions in the avian gut: Impacts on health and productivity. *Poultry Science*, 93(1), 34-47.
20. Trompette, A., Gollwitzer, E. S., &Yadava, K. (2022). Gut microbiota influences immune tolerance and asthma risk. *Nature Immunology*, 15(7), 768-776.
21. Zhao, L., Huang, Y., & Lu, J. (2023). Probiotic and prebiotic supplementation as a strategy to improve livestock health. *Journal of Animal Science*, 101(3), 532-545.
22. Ríos-Covian, D., Gueimonde, M., & Salazar, N. (2022). Targeting the gut microbiota in animal health: Therapeutic perspectives. *Animal Microbiome*, 4(5), 32-45.
23. Hou, K., Wu, Z. X., Chen, X. Y., Wang, J. Q., Zhang, D., Xiao, C., ... & Chen, Z. S. (2022). Microbiota in health and diseases. *Signal transduction and targeted therapy*, *7*(1), 1-28.
24. Kalbermatter, C., Fernandez Trigo, N., Christensen, S., &Ganal-Vonarburg, S. C. (2021). Maternal microbiota, early life colonization and breast milk drive immune development in the newborn. *Frontiers in immunology*, *12*, 683022.
25. Amenyogbe, N., Kollmann, T. R., & Ben-Othman, R. (2017). Early-life host–microbiome interphase: the key frontier for immune development. *Frontiers in pediatrics*, *5*, 111.