Received: 13 November 2020 Revised: 21 October 2021 Accepted article published: 14 November 2021 Published online in Wiley Online Library: 27 November 2021

(wileyonlinelibrary.com) DOI 10.1002/jsfa.11643

Influence of microbial probiotics on ruminant health and nutrition: sources, mode of action and implications

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Abstract

Globally, ruminant production contributes immensely to the supply of the highest quality and quantity of proteins for human consumption, sustenance of livelihoods, and attainment of food security. Nevertheless, the phasing out of antibiotics in animal production has posed a myriad of challenges, including poor growth, performance and nutrient utilization, pathogen colonization, dysbiosis, and food safety issues in ruminants. Probiotics (direct-fed microbials), comprising live microbial strains that confer health and nutritional benefits to the host when administered in appropriate quantities, are emerging as a viable, safe, natural and sustainable alternative to antibiotics. Although the mechanisms of action exerted by probiotics on ruminants are not well elucidated, dietary probiotic dosage to ruminants enhances development and maturation, growth and performance, milk production and composition, nutrient digestibility, feed efficiency, pathogen reduction, and mitigation of gastrointestinal diseases. However, the beneficial response to probiotic supplementation in ruminants is not consistent, being dependent on the microbial strain selected, combination of strains, dose, time and frequency of supplementation, diet, animal breed, physiological stage, husbandry practice, and farm management. Nonetheless, several studies have recently reported beneficial effects of probiotics on ruminant performance, health and production. This review conclusively re-iterates the need for probiotics inclusion for the sustainability of ruminant production. Considering the role that ruminants play in food production and employment, global acceptance of sustainable ruminant production through supplementation with probiotics will undoubtedly ensure food security and food safety for the world.

Keywords: probiotics; nutrition; ruminant; health; food security

INTRODUCTION

Apart from the production of high-quality protein in sufficient quantities for human consumption, sustenance of livelihoods (especially amongst rural dwellers) and contribution to food security comprise the other important roles of animal husbandry and production.[1] Livestock also provide draught animal power to millions of disadvantaged, marginal and smallholder farmers, mostly in developing countries, for both cultivation of farmlands and small-scale transport. Also, the manure produced by these animals is often used as biofuel and biofertilizer.[2,3] With the projected increase in the global population to nine billion people in 2050[4] and global economic growth and urbanization,[5] the increasing demand for livestock products, including meat, milk and eggs, is putting immense pressure on the livestock industry to continuously meet global expectations in production despite scarce resources.[2] There is a need for the development of a sustainable global animal production that will make the most efficient use of limited resources for the production of food and conserving the environment.

The importance of ruminants in the production of high-quality protein (meat and milk) and their ability to efficiently utilize fibrous feeds cannot be overemphasized. In comparison with other livestock species, ruminants are the primary food source for humans, especially in the developing parts of the world most affected by desertification and scarce fertile agricultural soils.[6] Furthermore, ruminants occupy the largest land area globally and have considerable influence on the environment through their emission of greenhouse gases, including carbon dioxide, methane and nitrous oxide.[7,8] Over the years, antibiotics have

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been used in the livestock industry at both prophylactic and subtherapeutic levels to enhance animal production (growth performance) and also to mitigate infectious diseases.[9] Nevertheless, with the phasing out of antibiotics in animal production, as a result of immense public health concerns, including the presence of drug residues in animal products,[1,10,11] the emergence and spread of resistance, and dysbiosis of gut microflora, there is a need for the application of naturally safe alternatives that will both improve animal growth performance as well as mitigate infectious diseases.

Probiotics or direct-fed microbials (DFM) are now widely accepted as safe and sustainable alternatives to antibiotics in animal production. The significant effects of probiotic supplementation as alternatives to antibiotics in animal production have been reported, as reviewed previously.[12] Probiotics can act by ameliorating enteric infections through the competitive exclusion of pathogens, mitigating chronic inflammatory and allergic diseases via immunomodulation and immune-stimulation, increasing digestibility and nutrient assimilation, improving the intake of dry matter to feed conversion ratio, reducing the emission of greenhouse gases, promoting growth and health performance, and improving ruminant meat and milk production.[12-16] The activities of probiotics can vary and mostly depend on both intrinsic and extrinsic factors, including the specific probiotic strain in use, dose, host species, probiotic strain combination (for multi-strain probiotics), environmental factors, husbandry practices and farm management.[1]

This review examines current knowledge and the concept of probiotic supplementation in ruminant production. It further explores the mechanisms of action, as well as the specific influence that probiotics exert on ruminants, including development and maturation, growth and performance, milk production and composition, nutrient digestibility and feed efficiency, haemato-biochemical parameters, pathogen reduction, and mitigation of gastrointestinal diseases. The review also discusses the sources, features and administration of ruminant probiotics, and, finally, the inclusion of probiotics in the sustainability of ruminant production as the biological strategy for global food security and food safety.

PROBIOTICS: CONCEPT AND STRAINS

Concept of probiotics and their strains

Over the years, researchers have proposed many definitions for the term "probiotic" based on the beneficial and health outcomes obtained as a result of the application of certain microbial strain(s) in different host species. Kollath, in 1953,[17] initially used the term "probiotic" to generally describe inorganic and organic substances that were considered to restore the health of malnourished patients. Lilly and Stillwell, in 1965,[18] further expanded the term "probiotic" to mean "unknown substances" produced by certain ciliate protozoa, which enhanced the survival and development of other protozoa. Subsequently, Parker, in 1974,[19] further included both living organisms and non-living substances in his definition of probiotics to be "organisms and substances which contribute to intestinal microbial balance". The increasing application of probiotics in feed supplementation in livestock production led to the reconsideration of probiotics as "alive microbial feed supplement which beneficially affects the host animal by improving its intestinal microbial balance".[20] Other researchers defined probiotics as "live cultures of microorganisms that are deliberately introduced into the rumen to improve animal health or nutrition".[21] With the massive production and commercialization of probiotics for livestock production, the Food and Drug Administration of the United States requires manufacturers of livestock feeds to replace the term "probiotic" with the phrase "direct-fed microbial" (i.e. DFM).[22] DFM has been defined as "alive, naturally occurring microorganisms that have been used to improve the digestive function of livestock".[23,24]

The broader perspectives in the definition and concept of DFM included a broad spectrum of microorganisms, such as bacteria, yeast, fungi, fragments of microbial cells and microbial secretions.[25-29] Microbial strains used as DFM flourish in the rumen of livestock and modulate the microflora and fermentation activities to benefit the host.[30] However, the increasing interest generated in probiotic science and a progressive understanding of probiotic action led to modification of the definition of a probiotic. The current and widely accepted definition of the term probiotic was proposed by a joint Food and Agriculture Organization and World Health Organization working group, who defined probiotics as "live microbial strains that, when administered in adequate amounts, confer a health benefit on the host".[31]

In ruminant production, the specific probiotics used as DFM include different bacterial and fungal species such as *Bacillus*, *Bifidobacterium*, *Enterococcus*, *Lactobacillus*, *Propionibacterium*, *Megasphaera elsdenii* and *Prevotella bryantii*, as well as strains of *Aspergillus* and *Saccharomyces*, respectively.[30,32] Nevertheless, strains of lactic acid bacteria (LAB) including *Lactobacillus*, *Bifidobacterium and Streptococcus*, have gained predominance and are mostly the widely used species as probiotic strains in the supplementation of ruminant feed.[33] It is noteworthy to add that many of the microbial strains used as ruminant probiotics exist naturally in the gastrointestinal tract of healthy animals but are often disrupted by both intrinsic and extrinsic stress factors on the host species.[33]

Ruminant probiotic products are usually comprised of mono- and/or multi-strains or multi-species. Also, allochthonous microorganisms, such as yeasts which are normally absent in the ruminant gastrointestinal tract (GIT) are used as probiotics, mostly in combination with microbial species such as *Bifidobacterium* and *Lactobacillus*, which are regarded as indigenous inhabitants of the ruminant gut.[2] Probiotics mainly composed of bacteria are effective in young ruminants, whereas studies have shown that fungal probiotics exert their beneficial effects mostly in adult ruminants.[34]

Ideal probiotic characteristics

There are many criteria for the selection of probiotics. First, microbial strains to be used as probiotics must successfully pass different *in vitro* evaluations before they can be approved for *in vivo* use. An effective and ideal probiotic is expected to function efficiently under a wide variety of conditions, including industrial processes and also in the gastrointestinal tract. There are a variety of parameters used for the screening and evaluation of probiotics, depending on the intended purpose and application of the microbial strain(s) in the target host(s).[35,36]

The initial and major step in the choice of a potential probiotic strain is the identification of its taxonomic class, which may indicate the domain and physiology of the specific strain. These features have immense effects on the choice of potential and novel probiotic strains.[37] Nevertheless, the effectiveness exhibited by a microbial strain intended for use as a probiotic is more important than the origin or source of such a strain.[31] Also, because a single probiotic strain is unlikely to possess all the equally suitable health benefits, combining suitable multiple strains with synergistic effects is often better.[38]

The microbial strain(s) to be used as probiotic either for humans or animals must be (i) identified to species and strain levels; (ii) examined for antimicrobial susceptibility; (iii) characterized for antimicribial production; (vi) examined for toxicity and pathogenicity; and (v) compatible with other authorized addiditives (where necessary).[39]

Probiotic sources and administration in ruminants

The source and origin of probiotic strains are directly dependent on the intended use and application of such probiotics. Generally, probiotics can be of animal or human origin or from food sources such as raw milk or fermented foods.[40] It was reported that the microflora of neonatal animals reflects the bacterial composition that they consumed primarily from fresh maternal milk. As such, ruminants' milk may be a repository of natural microbiota and could be used primarily for probiotics isolation. Furthermore, microbial strains intended to be used as probiotics should be appropriately isolated and identified before use.[41,42] Nevertheless, a report on probiotics from the Food and Agriculture Organization[31] rated the specificity and functionality of probiotic action above the source of probiotic microorganisms.

Probiotics can be administered through different routes. However, oral and vagina routes are often used.[43] The major route for the administration of probiotics in ruminants is via the oral cavity.[44-48] Additionally, recent studies report probiotics administration through the vaginal of ruminants. For example, Deng *et al*.[49] administered a mixture of lactic acid bacteria (LAB) probiotics to periparturient cows through intravaginal infusion.

MODE OF PROBIOTIC ACTION IN RUMINANTS

The advent of high-throughput molecular techniques has made it easier to obtain a better understanding of the diversity and mechanisms of action of probiotic strains in their host. The detailed mechanisms of probiotic action in ruminants have not been clearly and fully understood to date. However, several studies have illustrated some major processes used by probiotics in exerting their benefits on ruminants.[44,45,50,51] These mechanisms are specific to bacterial and fungal probiotics or their combinations.

Bacterial probiotics

As previously stated, strains of *Bifidobacterium* and *Lactobacillus* spp. are the major bacterial probiotics used in ruminant diets. The mode of action of these bacterial strains used as ruminant probiotics solely depends on the specific strain(s) of bacteria selected, dosages, frequencies and times of supplementation, and, to some extent, farm management. Although some probiotic strains act mainly with the rumen, other specifically impact the GIT of ruminants.[52]

Bacterial probiotic action within the ruminant rumen

Although not well elucidated, the action of probiotics within the rumen primarily depends on the LAB and lactic acid utilizing bacteria (LUB).[53] LAB produce organic acids that beneficially mitigate acidosis within the rumen, most especially in dairy cows by stimulating the growth of beneficial microbes and LUB.[29,54] LUB act by decreasing lactic acid concentration within the rumen hence, maintaining a steady pH in the rumen. When ruminants feed on fermentable diets, lactate is produced in large amounts in their rumen.[55] Certain bacteria, such as *Megasphaera elsdenii*, utilize the accumulated lactate, thereby impeding acidosis, which may be detrimental to the animal.[56] Ruminants harbor *Propionibacteria* in great numbers within their rumen, and these bacteria efficiently act on ruminant diets that are composed mainly of forage and concentrate.[55] Strains of *Propionibacteria* improve fermentation with a consequential increase in the production of propionate in the rumen.[57] During ruminal fermentation in early lactation, *Propionibacteria* convert lactate to propionate,[55] which leads to an increased production of liver glucose, making substrates available for lactose synthesis, hence reducing ketosis at the same time as improving energy efficiency.[57,58] Propionate accounts for the release of approximately 61–67% of glucose in lactating cows and growing ruminants.[59] The decrease in the emission of greenhouse gas, especially methane, by ruminants has been reported to be the result of an increase in ruminal propionate.[60] Although not well understood, Ghorbani *et al*.[61] reported that the inclusion of *Propionibacteria* strains as DFM in ruminants' diets decreased the numbers of amylolytic bacteria at the same time as increasing the population of *Entodinium* (protozoa) in the rumen of feedlot steers.

The overall efficiency and functionality of bacterial strains used as ruminant probiotics, either as mono- and/or multi-strains or species, can mostly be determined by their effect on the microflora in the rumen.[62,63] Furthermore, major environmental factors, including the quantity of lactic acid and volatile fatty acids (VFA), as well as pH, also determine the survival of microbes in the rumen.[64,65]

Bacterial probiotic action within post-ruminal GIT

Over the years, researchers have extensively explored the benefits exerted by bacterial probiotics and their mechanisms of action on the post-ruminal GIT.[30] The major modes of probiotic action within the post-ruminal GIT are as discussed below.

(1) Competitive exclusion of pathogens from adhering to intestinal mucosa. One of the mechanisms considered to be the most important and beneficial, which is exhibited by probiotic bacteria, is the competitive exclusion of pathogens.[66] This is based on the ability of bacteria to interact with each other and compete for nutrients and adhesion sites on the intestinal mucosa. Beneficial bacteria gain competitive advantage by modifying and rendering their microenvironment unsuitable for their competitors, mostly pathogens.[67] Frizzo *et al*.[68] showed how LAB used as probiotics adhered to the gut and protected animals against *Salmonella*. Also, the adhesion of enteropathogenic *Escherichia coli* and enterotoxigenic *Klebsiella pneumoniae* to intestinal mucosa were significantly reduced through the inclusion of *Lactobacillus rhamnosus* (Lcr35) as DFM.[69]
(2) Secretion of antimicrobial substances. Once probiotic strains are established within the gut, they can synthesize substances with either bacteriostatic or bactericidal properties such as bacteriocins, hydrogen peroxide and short chain fatty acids, as well as several organic acids. These substances secreted by probiotics, as well as the lowered intestinal pH, are detrimental and harmful to intestinal pathogens.[70] Bacteriocins antagonize pathogens within the GIT by interfering with DNA replication of target pathogens.[71] Most bacterial species, including *Bacillus* spp., LAB and bifidobacteria used as probiotics,[72,73] are capable of producing several types of thermostable bacteriocins[74] with a wide range of antimicrobial

activity against potential animal pathogens including *Bacillus cereus*, *Staphylococcus*, *Enterococcus*, *Listeria* and different species of *Salmonella*.[75]

(3) Immunomodulation and immune-stimulation. The immune system component of the gut, which protects the host from different types of antigens in the lumen of the GIT, can be affected by probiotics. Probiotic action within the intestinal tract modulates both the innate and adaptive immunity of the animal.[2] The ability of probiotics to adhere to the intestinal mucosa creates a natural barrier against potential pathogens and, in some instances, enhances the host immunity. Probiotics stimulate the immune system by increasing the synthesis and secretion of immunoglobulins, as well as macrophage and lymphocyte activities, and also by stimulating γ-interferon production.[24] *Lactobacillus casei* Shirota and *L. rhamnosus* Lr23 are known probiotics strains that stimulate macrophages to secrete tumor necrosis factor-α when used in ruminants.[76] Although the pro-inflammatory effect exerted by probiotics could positively impact the animal by mitigating potential pathogens from the GIT, it could also pose a negative impact by creating a pro-inflammatory environment that may damage the entire animal.

(4) Colonization resistance. Microorganisms colonizing the GIT of neonatal ruminants generally originate from the adult. These young ruminants become protected against intestinal pathogens by these colonizing microorganisms. Nevertheless, the intensive ruminant production has reduced this natural microbial colonization of the gut, hence rendering animals more susceptible to pathogen challenges in the GIT. In neonates, probiotics could mimic natural colonization, or colonize adult animals, thus shielding the intestinal mucosa from colonization by pathogenic organisms.[2] The presence of hydrophobic surface layer proteins in most probiotic strains, especially *Bifidobacterium* and *Lactobacillus* spp., enables them to adhere to the surface of their host enterocytes.[77] These adhering probiotic strains bind to certain receptor sites on the intestinal epithelium thereby preventing pathogens from accessing and colonizing intestinal epithelial cell surfaces.[77,78]

(5) Alteration in pathogenicity and virulence gene expression of pathogens. Cell to cell communication in bacteria through auto-inducers (secretory chemical signals) affects bacterial physiology.[79] Quorum sensing, one process of bacterial communication, is also used for communication between bacteria and their host.[80] Through quorum sensing, probiotics can influence the virulence and pathogenicity of pathogens. The ability of enterohaemorrhagic *E. coli* serotype O157:H7 to secrete extracellular autoinducer-2 was reported to be sustantially inhibited by fermentation products from *Lactobacillus acidophilus* La-5, which suppressed the expression of the locus of enterocyte effacement (LEE) virulence gene in *E. coli* serotype O157:H7. Consequently, quorum sensing can become disrupted so that colonization and pathogenesis by *E. coli* serotype O157:H7 in the GIT is prevented.[81] Using experimental rats, *Lactobacillus salivarius* decreased the expression of *Listeria monocytogenes* virulence gene, listeriolysin O in intestinal villi and Peyer's patches. Also, both *Lactococcus lactis* and *L. salivarius* lowered the *Listeria* count in spleens.[82] Likewise, Dong *et al.*[83] reported repression in the expression of three virulence genes of *L. monocytogenes*, including InlA, InlB and prfA, after treatment with *Lactobacillus plantarum* CICC6257.

Fungal and yeast probiotics

Because of the role of fungi in the stimulation of ruminal fermentation, fungal probiotics have been used extensively in ruminants.[53] Strains of *Saccharomyces* and *Aspergillus* are the most common fungal probiotics used in ruminants.[52] The inclusion of fungal-based probiotics in ruminant diets stabilizes the pH of the rumen, with a significant increase in total VFAs and a reduction in the concentration of ammonia.[26,84,85] The presence of yeast in the rumen also stimulates the enzymatic activity and growth of cellulolytic bacteria, in addition to improving the digestion of high-fiber diets and microbial translation of mRNA to proteins.[86] The DFM have been shown to reduce the redox potential in the rumen, thereby creating a desirable environment for the growth and survival of strict anaerobic organisms that often secrete vitamins, fatty acids and other factors stimulating ruminal microbial biomass synthesis.[87,88] The use of yeast DFM has been shown to mitigate rumen acidosis, as well as enhance the activity of LUB, especially *Selenomonas ruminantium*.[89] When used as ruminant probiotics, yeast mainly acts by improving the digestion of high fiber and concentrate diets, enhancing feed efficiency and also stimulating rumen fermentation.[53,84] More work is needed to fully unravel the detailed mechanisms of action used by fungal-based probiotics in improving ruminant production.

PROBIOTICS IN RUMINANT NUTRITION

Effects of probiotics on ruminants

The application of probiotics in ruminants has yielded significant results, especially with respect to boosting their health status, as well as enhancing productivity and their general performance. Researchers have concentrated more on the application of ruminant probiotics in the pre-ruminant's life and, to some extent, in adult ruminants. Over the years, studies have centered mostly on aspects of ruminants' health, including the control of pathogen carriage, infectious disease mitigation (mostly entero-diseases and mastitis), reduction of the severity of diarrhoea, and economic parameters such as the reduction of feed intake and feed conversion ratio. The dominant ruminant species investigated for probiotic applications are calves, goats and, to some extent, lambs/ewes.

Development and maturation of ruminants

With the application of dietary supplementation of probiotics in ruminants, several microbial strains, including *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, *Streptococcus* and *Propionibacterium* spp., have been successfully used for promoting the health, development and maturation of juvenile ruminants.[23,68,71,90-92] The enhancement of growth, development and maturation of neonatal ruminants as a result of probiotic supplementation has gained increased merit in animal production.[91] Neonatal calves are highly vulnerable to pathogens before and during weaning. During weaning, calves become highly susceptible to pathogen colonization in their gut as a result of their immature gut microbiota and a sudden change in feed composition.[25,93] The rapid adaptation to the change in feed composition and rapid colonization of beneficial microorganisms within the GIT of calves is of immense importance in ruminant maturation and development.[23] This crucial developmental stage prevents the colonization of enteropathogens within the GIT of calves. These enteropathogens are responsible for diarrhoea in calves that can result in a huge economic costs.[23] Apart from the impact of colostrum (maternal first milk) in ruminants, the introduction of probiotics into the immature

GIT of young ruminants can promote health.[91] At birth, microbial colonization of the gut increases, and the maturation of gut microflora and the intestinal mucosa proceeds gradually.[94] Shortly after birth, calves receive beneficial microorganisms, such as *Lactobacillus* spp., *Enterococcus* spp. and non-pathogenic *E. coli* before the incorporation of other microbial strains (mainly anaerobes) into the forestomach gut.[92] Maternal milk, maternal gut microflora and the environment are the primary sources of probiotic microorganisms for neonatal calves.[91,94] Maternal milk contains antibodies, lactoferrin, κ-casein, oligosaccharides and other proteins that stimulate the growth of *Bifidobacterium* spp. and other probiotic microorganisms within the gut and also antagonize potential pathogens.[95] The growth of these beneficial microorganisms in the gut facilitates the ability of young ruminants to digest high fiber diets at the same time as supporting their overall development and maturation[91] (Table 1).

Growth and performance

The supplementation of ruminants with specific mono- and/or multi-strain probiotics has been shown to significantly increase their growth and overall performance, including daily body weight, body weight gain and feed efficiency.[23,30,96] Although the effects of probiotics on the growth and performance of ruminants may vary, scientific investigations suggest that an increase and modulation of the intestinal microflora, as well as stimulation of the activities of cellulolytic bacteria that enhance digestion and absorption of nutrients, comprise the main modes of action exhibited by probiotics aimed at promoting growth and performance.[25,85,97-99]

The supplementation of cattle, goats and sheep with probiotics has led to better performance, improved feed intake and efficiency and weight gain.[44,45,50,57,96,100] The inclusion of *Pediococcus acidilactici* and *Pediococcus pentosaceus* in the diet of lambs during the post-weaning period significantly improved their average daily weight gain (+25.2 g per lamb), final body weight (+3.16 kg) and feed conversion ratio (FCR, −1.18).[101] However, the supplementation of small ruminants with probiotics can improve FCR.[56] Dietary inclusion of live yeast in beef cattle and dairy cows reportedly improved FCR, average daily gain, feed intake and final weight.[25,57,100,102] The inclusion of multi-species probiotics, containing *Lactobacillus*, *Streptococcus*, *Aspergillus* and *Saccharomyces cerevisiae*, in the diet of growing lambs significantly increased the average daily weight gain by 7.2%.[103] Moreover, Mudgal and Baghel[104] reported a 31.4% increase in the average daily weight gain of buffalo calves fed with diets containing *L. acidophilus*.

Nevertheless, some studies recently reported divergent findings, showing that no effect was exerted on the growth and performance of ruminants supplemented with probiotics.[45,46,50] The difference in the microbial strains used as probiotics, the number of cells used (dose), ruminant species and breed, environmental factors, feeding practice, farm management, and other variables may account for their contrary results.[30,96] As shown in Table 1, probiotic effects are species-specific and host-dependent.[43,105,106]

Milk composition and milk production

The inclusion of probiotics in the feeding of livestock may not only improve health status, but may also ensure food security and food safety.[107] The supplementation of ruminants with probiotics has been shown to increase milk production, milk quality and milk composition, with a higher presence of functional components such as protein, fat and solid non-fat and a lower count of somatic cells.[23,33,100,108,109] The inclusion of *S. cerevisiae* and *Aspergillus oryzae* in the diets of dairy cows significantly increased milk production, with a greater concentration of milk proteins.[110] Ruminal fermentation and milk production also improved when dairy cows were supplemented with strains of *Bacillus subtilis* as probiotics.[111,112] Also, Stella *et al*.[113] reported a 14.0% increase in the average daily milk yield among lactating Saanen dairy goats fed with 4×10^9 cfu day^{-1} per animal of *S. cerevisiae*.

The overall findings of a meta-analysis on the effects of a *S. cerevisiae* probiotic strain on milk production, feed intake and the rumen fermentation of buffaloes, cattle, goats and sheep showed a significant increase in milk yield.[114] Similarly, there was an approximate 8.0% increase (i.e. 1.1 kg day^{-1}) of milk yield by Tunisian Holstein Friesian cows supplemented with yeast probiotics compared to the control.[115] From the same experiment, the probiotic supplemented cows had higher protein (41.7 g per cow per day) and milk fat (53 g per cow per day) levels than the control animals (38.7 and 47 g per cow per day). Different mechanisms have been reported to explain the increases in milk yield in response to probiotic supplementation. On the one hand, it has been reported that increases in milk yield result from the ability of probiotic strains to reduce inflammation of the udder and thus suppress the number of somatic cells in milk.[109] On the other hand, other studies have postulated that improvements in milk production and composition are the result of probiotics with respect to stimulating growth and an increase in the population of both fiber-degrading and cellulolytic-degrading bacteria[116] (Table 1).

Feed efficiency and nutrient digestibility

Improvement in ruminant growth and overall performance as a result of probiotic supplementation is often associated with improvement in fiber degradation, feed intake, nutrient digestibility and ruminal digestion.[23,117-119] As a complex carbohydrate and usually non-digestible by mammalian enzymes, fiber, being the major component of plants, is mainly composed of cellulose, hemicellulose and lignin.[120,121] Between 15% and 70% of diets fed to ruminants are composed of cellulose and hemicellulose.[122] The ability of probiotics to improve nutrient digestibility and feed intake in ruminants may be attributed to the enhanced proliferation and growth of ruminal cellulolytic bacteria and the prevention of acidosis in the rumen.[123] The supplementation of lactating cows with yeast increased the frequency of feed intake, fiber degradation and nutrient digestibility in the rumen.[25] Feeding Awassi lambs with yeast culture has been reported to increase the digestibility of dry matter (676 g kg^{-1}), crude protein (653 g kg^{-1}), organic matter (683 g kg^{-1}) and neutral detergent fiber (which is the most common measure of fiber used for animal feed analysis) (561 g kg^{-1}) compared to the control.[124] Digestion of acid and neutral detergent fiber, as well as levels of crude protein, improved after lactating Holstein cows were supplemented with a diet containing strains of *Lactobacillus acidophilus* NP51 and *Propionibacterium freudenreichii* NP24.[125] Azzaz *et al*.[126] reported improved digestibility of organic matter, dry matter, crude fiber, crude protein and nitrogen-free extract in goats fed with diets containing *L. acidophilus* and *Aspergillus awamori*. The inclusion of dried live yeast significantly improved the digestibility of fiber, dry matter and crude protein in lambs fed diets comprised of concentrates and roughages at a 60:40 ratio in the dry matter.[127] Nevertheless, variations in probiotic species and strains, dosage, feed composition, feeding systems and

Table 1. Summary of probiotics effects on ruminant nutrition and performance

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
Bio-Plus 2B®, Chr. (Hansen A/S)	*Bacillus subtilis*, *B. licheniformis*	132×10^9 cfu kg^{-1}	1. Increased growth rate 2. Increased feed intake 3. Increased average daily gain	Calves	39,153
Cernivet LBC (Cerbios)	*Enterococcus faecium*	2×10^{10} cfu g^{-1})	1. Increased growth rate 2. Increased forage and total dry matter intake 3. Increased average weight gain 4. Increased daily weight gain	Lithuanian Black-and-White calves	132
Cylactin (DSM)	*E. faecium*	70 g kg^{-1}	1. Improved feed efficiency during pre-weaning 2. Increased average daily gain 3. Greater intake of crude protein and neutral detergent fiber	Holstein calves	154
Protexin® (Protexin)	*Lactobacillus plantarum*, *L. bulgaricus*, *L. acidophilus*, *L. rhamnosus*, *Bifidobacterium bifidum*, *Streptococcus thermophilus*, *E. faecium*, *Aspergillus oryza and Candida pintolopesii*	2×10^8 cfu g^{-1}	1. Increase in average daily gain 2. Increase in feed intake 3. Increase LAB count	Holstein female calves	155
Oralin® (Chevita GmbH)	*E. faecium* DSM 10663	1.5×10^7 cfu g^{-1}	1. Control dysbiosis and intestinal disturbances 2. Reconstituted the gut flora after antibiotic therapy	Calves	2
PrimaLac (Star Labs, Inc.)	*B. bifidium*, *B. thermophilus*, *E. faecium*, *L. acidophilus*, *L. casei*,	2.5×10^7 cfu g^{-1}	1. Higher milk yield 2. Increased milk components (lactose, protein and fat) 3. Increased aspartate aminotransferase activity in blood plasma	Cattle (beef, dairy), deer, ewe	156
Biovet –YC Gold (Biovet Health Products)	*L. acidophilus*, *Saccharomyces cerevisiae*, *S. boulardii and Propionibacterium frendenreichii*	20 g day^{-1} cow^{-1}	1. Increased milk production of lactating cows 2. Higher Milk fat, milk protein and Solids-Not Fat content	Calves	33
No information provided	*L. casei*	1.0×10^7 cfu g cow^{-1} day^{-1}	1. Increased the resistance of animals to adverse environmental conditions (high temperature and humidity) 2. Increased milk yield in summer and winter	Holstein-Friesian milk cow	157

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
Pro-Biotyk EM15® (ProBiotics)	*B. subtilis*, *B. animalis*, *B. bifidum*, *B. longum*, *L. acidophilus*, *L. casei*, *delbrueckii* subsp. *bulgaricus*, *L. fermentum*, *L. plantarum*, *L. lactis* subsp. *Lactis*, *S. cerevisiae*, *S. thermophilus*	20 cfu mL^{-1}	1. Improved feed digestibility 2. Decreased emission of gases such as ammonia, hydrogen sulphide and mercaptans. 3. Improved balance of the microflora in the digestive tract,	Cattel, lambs, Calves	158
Pro-Biotyk EM15® (ProBiotics)	*B. subtilis*, *B. animalis*, *B. bifidum*, *B. longum*, *L. acidophilus*, *L. casei*, *L. delbrueckii* subsp. *bulgaricus*, *L. fermentum*, *L. plantarum*, *L. lactis* subsp. *lactis*, *S. cerevisiae*, *S. thermophilus*	20 mL L^{-1} water	1. Improved balance of the microflora in the digestive tract, 2. Reduction and stabilization of somatic cells in milk. 3. Improved immunity	Cattel, lambs, Calves	158
Yea Sacc (Alltech)	*S. cerevisiae*	1×10^9 cfu cow^{-1} day^{-1}	1. Improved milk production and milk quality 2. Increased energy corrected milk production 3. increased synthesis of milk protein, milk protein content, and milk urea content 4. Lower milk fat content 5. Higher lactose content 6. Enhanced energy utilization 7. Reduced methane emissions	lactating dairy cows	159
Yea-Sacc-1026 (Alltech)	*S. cerevisiae*	1×10^9 cfu $head^{-1}$	1. Improved milk quality (fat and protein content) 2. Increased body weight of lambs	Lambs	73
Yea-Sacc-1026 (Alltech)	*S. cerevisiae*	2.5×10^9 cfu g^{-1}	1. Improved feed efficiency 2. Increased dry matter digestibility	Dairy Holstein heifers	168
Yea-Sacc-1026 (Alltech)	*S. cerevisiae*	4.5×10^9 cfu	1. Increased in dry matter intake 2. Increased digestion of non-digestible fiber And hemicellulose digestibility	Holstein heifers	168
Yea-Sacc-1026 (Alltech)	*S. cerevisiae*	2.5×10^9 cfu g^{-1} yeast	1. Improved metabolic status	Multiparous dairy cows	169
No information provided	*L. acidophilus*, *L. salivarius*, *L. reuteri*	2.3×10^7 cfu cow^{-1} day^{-1}	1. Improved metabolic activity 2. Increased body weight	Maltese goat kids	143
No information provided	*B. licheniformis*, *B. subtilis*	1×10^7 cfu mL^{-1}	1. Increased milk yield 2. Higher milk quality 3. Increased body weight	Lambs	116

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
No information provided	*Aspergillus oryzae*	10^9 cfu mL^{-1}	1. increased production of milk 2. Increased ratio of protein and SNF in milk	Cows	110
No information provided	*A. oryzae*	5×10^7 cfu mL^{-1}	1. Higher total volatile fatty acids, propionate, and acetate concentrations in the rumen. 2. Higher counts of cellulolytic bacteria	Calves	160
No information provided	*L. acidophilus*	5×10^7 cfu mL^{-1}	1. Increased body weight	Calves	161
No information provided	*B. pseudolongum*, *L. acidophilus*	3×10^9 cfu mL^{-1}	1. Improved average daily gain 2. Improved feed efficiency	Calves	162
No information provided	*L. acidophilus*, *S. cerevisiae*	1×10^9 3×10^9 cfu $flask^{-1}$ kg^{-1}	1. Increased average daily gain 2. Improved feed efficiency	Calves	163
No information provided	*L. casei* DSPV 318 T *L. salivarius* DSPV 315 T *Pediococcus acidilactici* DSPV 006 T	3×10^9 cfu kg^{-1} live weight	1. Stimulated consumption of Starter 2. Early development of the rumen.	Calves	68
No information provided	*E. faecium*, *L. plantarum*, *S. cerevisiae*	from 1×10^5 cfu mL^{-1} to 1×10^7 cfu mL^{-1}	1. Improved digestion rate 2. Increased digestion of high moisture ear corn (HMEC) dry matter 3. Reduction in intestinal pH	Cows	54
No information provided	*Propionibacterium* P15 *E. faecium* EF212	1×10^9 cfu g^{-1}	1. improved intake of dry matter 2. Lowered blood CO_2 concentrations	Cows	61
No information provided	*E. faecium*, Yeast	5×10^9 cfu g^{-1} 5×10^9 cfu g^{-1}	1. Increased consumption of dry matter 2. Increased daily milk production	Cows	164
No information provided	*Propionibacterium* P169	6×10^{10} cfu cow^{-1} 6×10^{11} cfu cow^{-1}	1. Increased milk yield 2. Improved feed efficiency 2. Increase daily gain	Cows	57
No information provided	*L. acidophilus* LA747, *P. freudenreichii* PF24, *L. acidophilus* LA45	1×10^9 cfu cow^{-1} 2×10^9 cfu cow^{-1} 5×10^8 cfu cow^{-1}	1. Increased milk yield 2. increased fat corrected milk 3. Reduced ruminal pH and total VFA concentration in the rumen	Cows	165
No information provided	*E. faecium*, *S. cerevisiae*	5×10^9 cfu cow^{-1} day^{-1} 5×10^9 cfu cow day^{-1}	1. Increased in milk fat 2. Received fewer antibiotic treatments.	Cows	28
No information provided	*S. cerevisiae* subspecies *boulardii* CNCM I-1079	0.5 g of yeast $steer^{-1}$ day^{-1}	1. Treatments did not affect dry matter intake, average daily gain or feed efficiency during the experimental period.	Beef cattle	166

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
No information provided	*Prevotella bryantii*	2×10^{11} cfu dose^{-1}	1. Increased milk fat 2. Higher concentration of acetate, Butyrate 3. Decreased lactate concentration	Dairy cow	62
No information provided	*Propionibacterium* strain P169	6×10^{11} cfu day^{-1}	1. Lowered concentrations of acetate 2. Greater concentrations of propionate 3. Higher energetic efficiency	Cows	58
No information provided	*Propionibacterium* strain P169, yeast culture	6×10^{11} cfu steer $^{-1}$ day^{-1} 56 g steer^{-1} day^{-1}	1. Increased molar proportions of propionate 2. No effect on ruminal digestibility, microbial N synthesis, or particulate passage rates.	Beef cattle	167
No information provided	*B. licheniformis*, *B. subtilis*	2×10^{11} cfu dose^{-1}	1. Reduction in mortality 2. Increased milk production	Sheep and Lambs	116
	B. licheniformis, *B. subtilis*	2×10^{9} cfu cow^{-1} day^{-1}	1. Increased milk yield and milk protein 2. Increased ruminal digestibility 3. Increased total volatile fatty acids concentration	Holstein cows	111
No information provided	*B. licheniformis B. subtilis*	2×10^{9} cfu head^{-1} day^{-1}	1. higher average daily gain 2. Increased final live weight.	Holstein Calves	153
No information provided	*S. cerevisiae*, QAU03, (locally isolated yeast from *Sahiwal* cow dung sample)	3.13×10^{7} cfu g^{-1} yeast	1. Increased fiber digestibility 2. Improved milk and its fat contents 3. Improved gastrointestinal tract microbial balance	Lactating cows	168
Levucell Sc (Pasteur institute)	*S. cerevisiae* CNCM I-1077	1×10^{10} cfu head^{-1} day^{-1}	1. Enhanced rumen fermentation 2. Lowered CH4 emissions	Non-lactating dairy Holstein cows	87
Levucell Sc 20 (Pasteur institute)	Dry yeast (CNCM-1077	0.5 g head^{-1} day^{-1}	1. Decreased time spent in subacute rumen acidosis	Holstein dairy cows in late lactation	25
Levucell SC 10 ME (Pasteur institute)	*S. cerevisiae* CNCM I-1077	1×10^{10} cfu g^{-1} yeast	1. Lowered the risk of rumen acidosis 2. Increased fiber	Holstein dairy cows in Non-lactation	97

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
			degradation of low-quality maize silages		
Diamond-V XP yeast culture (Diamond-V)	*S. cerevisiae*	57 g day^{-1} $head^{-1}$	1. Increased dry matter and protein digestion 2. Increased propionate production 3. Decreased microbial protein	Lactating cows	170
A-Max yeast culture concentrate (A-Max)	*S. cerevisiae*	57 g day^{-1} $head^{-1}$	1. Increased dry matter protein digestion 2. Increased propionate percentage 3. Decreased rumen pH 4. Increased microbial nitrogen digestion	Lactating cows	170
BIOSAF SC 47 (Lesaffre Feed Additives)	*S. cerevisiae* Sc47	5 g day^{-1} $head^{-1}$	1. Increased volatile fatty acids concentrations 2. Reduction rumen pH 3. Increased counts of fibrolytic and lactate-using bacteria	Early lactating cows	171
Actisaf Sc 47 (Phileo by Lesaffre)	*S. cerevisiae*	10 g day^{-1} $head^{-1}$	1. Decreased acetate: propionate ratio 2. Decreased Bacteroidetes 3. Increased Fibrobacter bacteria	Mid-to-late lactating cows	172
No information provided	*Orpinomyces* strain KNGF-2	200 mL $head^{-1}$	1. Increased nutrient digestibility and nitrogen retention 2. Increased bacteria and fungi abundance	Mature sheep	173
No information provided	*Orpinomyces* spp. C-14, *Piromyces* spp. WNG-12	160 mL day^{-1} $head^{-1}$ for buffalo calves 250 mL $week^{-1}$ $head^{-1}$ for lactating buffaloes	1. Increased digestibility of dry matter, crude protein, non-digestible fibre and cellulose 2. Increased production of volatile fatty acids total nitrogen and trichloroacid precipitable nitrogen, 3. Decreased ruminal pH and ammonia nitrogen 3. Increased zoospores	Buffalo calves and lactating buffaloes	174,175
MTB-100 (Alltech)	Yeast-derived cell wall preparation	20, 40, or 60 g day^{-1} $head^{-1}$	1. Decreased ruminal indigestible 2. Decreased fescue toxicosis	Beef steers and cows	176
Solid powder (NA)	*S. cerevisiae* fermentation product	6 g kg^{-1} DMI	1. Decreased ruminal ammonia nitrogen 2. Decreased methane emissions	Growing goats	177
No information provided	*L. casei* ssp. *casei*	1×10^{8} cfu mL^{-1}	1. Increased weight gain	Calves	98

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
			2. Improved feed efficiency		
No information provided	Lactate-utilizing/or lactate-producing bacteria	1.3x10^{6} cfu mL^{-1}	1. Improved feed efficiency 2. Increased in daily gain	Cattle	23
No information provided	Live yeast	60 g day^{-1} head^{-1}	1. Improved average daily gain 2. Increased final weight 3. Increased feed Intake 3. Improved feed to gain ratio	Beef cattle	102
No information provided	Yeast	10 g day^{-1} head^{-1}	1. Increased milk yield and milk quality 2. Increased feed efficiency 3. Reduced ruminal acidosis	Dairy cows	57,100
No information provided	*L. casei* Zhang and *L. plantarum* P-8	1 × 10^{8} cfu mL^{-1}	1. Improved quality and quantity of milk production	Dairy cows	109
FasTrack Microbial pack (Conklin fastract)	*L. acidophilus*, *S. cerevisiae*, *E. faecium*, *A. oryzae*, active dry yeast culture	5 g day^{-1} head^{-1}	Improve body weight	Dairy cows	44,96
No information provided	*L. acidophilus*, *S. cerevisiae*, *S. boulardii*, *P. freudenreichii*	5 g day^{-1} head^{-1}	1. Increased milk production 2. Increased feed intake	Lactating cows	33
No information provided	*B. licheniformis* and *B. subtilis*	1 × 10^{8} cfu mL^{-1}	1. Reduced lamb mortality rate 2. Increased average daily 3. Milk yield per ewe 4. Improved fat and protein content of milk	Sheep	116
No information provided	*S. cerevisiae*	2.5 × 10^{6} cfu mL^{-1}	1. Increased in the mean protozoal count 2. Increased total bacterial count	Buffalo bulls	178
No information provided	Live Bacillus culture; *B. licheniformis*	100 g day^{-1}	1. Increased in microbial crude protein flow into duodenum 2. Decreased in ammonia nitrogen concentration in the ruminal fluid 3. Increased total volatile fatty acids and acetate concentrations in the ruminal fluid	Chinese Holstein cows	111

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
			4. Improved ruminal apparent nutrient digestibility of non-digestible fats		
No information provided	*Ruminococcus flavefaciens* NJ	1×10^6 cfu mL^{-1}	1. Increased abundance of cellulolytic bacterial populations in the rumen 2. Improved in sacco digestibility of Timothy hay with the high concentrate diet. 3. Increased in the persistence of beneficial bacteria *R. flavefaciens* NJ	Dairy cows	62
No information provided	A mixture of *L. plantarum*, *P. acidilactici*, *E. faecium* and *L. lactis*	5×10^5 cfu g^{-1} fresh herbage	1. Increased in lactic acid concentration 2. Decreased concentration of acetic acid. 2. Higher rumen microbe count 3. Lowered ratio of acetic acid to propionic acid. 4. Improved rumen protein synthesis 5. Higher content of protein nitrogen and total nitrogen in the rumen.	Dairy cows	179
No information provided	*P. acidilactici* and *P. pentosaceus*	1×10^8 cfu mL^{-1}	1. Improved average daily gain 2. Increased final body weight 3. Improved feed conversion ratio	Lambs during post-weaning period	101
No information provided	*L. acidophilus*	10^6 cfu mL^{-1}	Increased the average daily weight gain	buffalo calves	104
No information provided	*S. cerevisiae*	4×10^9 cfu day^{-1} animal^{-1}	Increased in the average daily milk yield	lactating Saanen dairy goats	113
No information provided	*L. acidophilus* and *A. awamori*	10^8 cfu mL^{-1}	Improved digestibility of organic matter, dry matter, crude fiber, crude protein and nitrogen-free extract	Goats	126
No information provided	*L. acidophilus* and *P. freudenreichii*	2.5×10^4 cfu mL^{-1}	Decreased incidences of diarrhoea and other diseases of GIT	lambs and calves	64

Table 1. Continued

Probiotic product (manufacturer)	Probiotic strain(s)	Probiotic dosage	Impacts	Animal species (host)	Reference
CSPB (calf specific probiotic) (Winclove)	*L. acidophil* W55, *L. salivarius* W57, *L. paracasei* spp. *paracasei* W56, *L. plantarum* W59, *L. lactis* W58, and *E. faecium* W54	1.0×10^9 cfu kg^{-1}	1. Enhanced growth rate 2. Increased body weight gain 3. Improved feed consumption 3. Decrease mortality	Veal calves	180
Lactoamylovorinum (NA)	*Lactobacillus* spp.	1 mL day^{-1} head^{-1}	1. Increased daily weight gain 2. Improved nutrient digestibility 3. Improved carcass quality 4. Increase carcass yield	Calves	181
No information provided	*L. acidophilus*, *L. jugarti*, *L. casei*	1.0×108 cfu kg^{-1}	1. Decreased the cost per unit gain in live weight 2. increased digestibility 3. Improved feed conversion and lower feed intake	Calves	41,182
No information provided	*L. acidophilus*	2.5×10^7 cfu	1. Improved daily weight gain 2. Improved feed conversion	Holstein calves	183
No information provided	*L. acidophilus*, *L. buchneri* 40 788	1×10^5, 5×10^5, or 1×10^6 cfu g^{-1}	1. Significantly increased milk production 2. Increased the concentration of acetic acid 3. Improved the aerobic stability of the ration in lactating cows 4. Increased milk production	Dairy cows, lactating cows	55
No information provided	*L. acidophilus*	10^7 cfu g^{-1}	1. Increased daily milk yields 2. Increased milk protein content	Cows	184
No information provided	*L. acidophilus*, *S. faecium*, *L. casei*, *L. fermentum* and *L. plantarum*	10^{10} cfu	1. Stimulated feed intake 2. Improved daily weight gain	Lambs	185

NA, Not available.

Table 2. Summary of probiotics effects on ruminant health

Probiotic product (Manufacturer)	Probiotic strain(s)	Probiotic dose	Impacts	Ruminant host	Reference
No information provided	*Lactobacillus acidophilus*, *Propionibacterium freudenreichii*	From 1×10^{6} cfu mL^{-1} to 1 × 109 cfu mL^{-1}	Lowered faecal shedding of *E. coli*	Calves	186
No information provided	*Bacillus cereus* var. Toyoi *Saccharomyces boulardii*	1.0×10^{8} cfu kg^{-1}	Both probiotics enhanced humoral immunity.	Sheep	187
No information provided	*Bacillus subtilis* strain 166	1×10^{9} cfu mL^{-1}	1. There were no significant differences observed between treatments for either hide or fecal prevalence of *E. coli* O157: H7.	Cattle	188
Calf-specific probiotic (NA)	*L. acidophilus* W55, *L. salivarius* W57, *L. paracasei* spp. *paracasei* W56, *L. plantarum* W59, *Lactococcus lactis* W58, and *Enterococcus faecium* W54.	1.0×10^{9} cfu kg^{-1}	1. Reduced diarrhea 2. Decreased fecal coliform counts	Veal calves	180
No information provided	*L. acidophilus*, *S. cerevisiae*, *E. faecium*, *Aspergillus oryzae*, *fructooligosaccharide*, active dry yeast culture	2.50×10^{8} cfu g^{-1}	1. Improved Packed cell volume 2. Increased Faffa Malan Chart (FAMACHA) scoresscores	Goats	50
No information provided	*L. acidophilus* and *P. freudenreichii*	1×10^{9} cfu mL^{-1}	1. Decreased incidences of diarrhoea 2. Decreased diseases of GIT	Lambs and calves	64
Cernivet LBC (Cerbios)	*E. faecium*	2.4 g day^{-1} calve^{-1}	1. Reduction in diarrhoea 2. Reduction in faecal count of clostridia and enterococci.	Calves	132
No information provided	*L. plantarum*, *bulgaricus*, *L. acidophilus*, *L. rhamnosus*, *Bifidobacterium bifidum*, *Streptococcus thermophilus*, *E. faceum*, *Aspergillus oryza* and *Candida pintolopesii*	3.08×10^{8} cfu g^{-1}	1. Controlled diarrhoea and bloat 2. Reduction of mortality 3. Reduction in veterinary cost of treatment	Holsten male calves	189
Protexin® (Protexin)	*L. plantarum*, *L. delbrueckii* subsp. *bulgaricus*, *L. acidophilus*, *L. rhamnosus*, *B. bifidum*, *S. salvarius* subsp. *thermophilus*, *E. faecium* and yeast	2×10^{8} cfu g^{-1}	1. Significantly lowered count of pathogenic *E. coli* 2. Mitigation of diarrhoea	Holstein female calves	155
Protexin (Protexin)	*L. plantarum*, *delbruecki* subsp. *bulgaricus*, *L. acidophilus*, *L. Rhamnosus*, *Bifidobacterium bifidum*, *S. salivarius* subsp. *thermophilus*, *E. faecium*, *A. oryzae*, *C. pintolepesii*	2 g day^{-1} head^{-1}	Significant decreased in ileocecal infection by *Mycobacterium avium* ssp. *paratuberculosis* (MAP)	Holstein bull calves	190

Table 2. Continued

Probiotic product (Manufacturer)	Probiotic strain(s)	Probiotic dose	Impacts	Ruminant host	Reference
No information provided	*L. casei*	1.0×10^7 cfu^{-1} g cow^{-1} day^{-1}	1. Decreased in the number of somatic cells 2. Decreased in the incidence of mastitis 3. Positive effect on the microflora of the gastrointestinal tract 3. Greater resistance to infectious diseases	Holstein-Friesian milk cow	157
No information provided	*L. acidophilus*	10^9 cfu steer^{-1} daily	Reduced *E. coli* O157 levels	Beef cattle, steer	131
No information provided	*L. acidophilus* strain NP 51	10^9 cfu steer^{-1} daily	Reduced *E. coli* O157 prevalence in both fecal and hide sample	Beef cattle	191
CSPB (calf specific probiotic) (Winclove)	*L. acidophil* W55, *L. salivarius* W57, *L. paracasei* spp. *paracasei* W56, *L. plantarum* W59, *L. lactis* W58, and *E. faecium* W54	1.0×10^9 cfu kg^{-1}	1. Decreased mortality 2. Reduced the incidence of diarrhea 3. Reduced faecal counts of coliforms 4. Reduction in the percentage of calves in need of therapy and the amount of treatments needed against digestive or respiratory diseases	Veal calves	180
No information provided	*L. acidophilus* NPC 747	1×10^9 cfu	1. Decreased but did not eliminated fecal shedding of *E. coli* O157:H7 2. Reduced *E. coli* O157:H7 contamination on hides	Cattle	192
No information provided	*L. gallinarum* LCB 12, *S. bovis*	1×10^{10} cfu	1. Reduced or stopped carriage of *E. coli* O157	Holstein calves	193,194
No information provided	*L. acidophilus*	2.5×10^7 cfu	Decreased diarrhea	Holstein calves	183
No information provided	*L. acidophilus*, *S. faecium*, *L. casei*, *L. fermentum* and *L. plantarum*	10^{10} cfu	Reduced fecal shedding of *E. coli* O157:H7	Lambs	185
No information provided	*B. pseudolongum*, *L. acidophilus*	3×10^9 cfu mL^{-1}	Reduction in diarrhea incidence	Calves	162
No information provided	*L. acidophilus*, *L. plantarum*, *L. acidophilus* 27SC	1.85×10^7 cfu mL^{-1}	1. Decreased incidence of diarrhea 2. Increased lactobacilli count in feces.	Calves	195
Oralin® (Chevita GmbH)	*E. faecium* DSM 10663	2.5×10^8 cfu mL^{-1}	1. Controlled dysbiosis and intestinal disturbances 2. Reconstituted the gut flora after antibiotic therapy	Calves	2

Table 2. Continued

Probiotic product (Manufacturer)	Probiotic strain(s)	Probiotic dose	Impacts	Ruminant host	Reference
Pro-Biotyk EM15® (ProBiotics)	*B. subtilis, B. animalis, B. bifidum, B. longum, L. acidophilus, L. casei, L. delbrueckii* subsp. *bulgaricus, L. fermentum, L. plantarum, L. lactis* subsp. *lactis, S. Cerevisiae, S. thermophilus*	20 mL L^{-1} water	1. Improved balance of the microflora in the digestive tract, 2. Reduction of diarrhea occurrence 3. Reduction and stabilization of somatic cells in milk. 3. Improved immunity and	Cattel, lambs, Calves	158
No information provided	*B. pseudolongum, L. acidophilus*	3×10^9 cfu mL^{-1}	1. Reduced diarrhea incidence.	Calves	162
No information provided	*Propionibacterium* P15, *E. faecium* EF212	1×10^9 cfu g^{-1}	1. Lowered blood CO_2 concentrations 3.. Reduced risk of metabolic acidosis.	Cow	63
No information provided	*B. subtilis*	10^8 cfu $head^{-1}$	Reduced *Clostridium perfringens* shedding	Holstein calves	(Wehnes *et al*.,196)
No information provided	*L. acidophilus* and *P. freudenreichii*	1×10^6 cfu mL^{-1}	1. Decreased incidences of diarrhea 2. Decreased in the occurrence of diseases of gastrointestinal tract	Lambs and calves	64

NA, Not available.

frequency, animal species, animal age and physiological state, environmental conditions, etc., can influence the effectiveness of probiotics in the improvement of nutrient digestibility and feed intake in ruminants[2,127] (Table 1).

Pathogen reduction and gastrointestinal disease mitigation

Apart from the fact that some ruminants are the primary reservoir host for some foodborne pathogens, outbreaks of some human diseases are linked to some ruminant species.[1,120,128] The transmission of these zoonotic pathogens from ruminants to humans constitute a serious public health problem with huge global economic loss.[1,128] In the last decade, scientists have increasingly sought out healthy and safe agricultural practices in livestock production, aimed at reducing the carriage of gut pathogens, their release unto the environment and their transmission to humans. Major zoonotic pathogens that have been targeted are *E. coli*, *E. coli O157*, *Campylobacter*, *Enterococcus*, *Listeria*, *Salmonella* and *Shigella* spp.[25,128] The dietary inclusion of probiotics has been shown to reduce the enteric colonization of pathogens in ruminants, which enhance overall animal health, as well as prevent human transmission and environmental contamination[2,30,129,130] (Table 2).

LAB, especially strains of *L. acidophilus*, used in feedlot cattle have been shown to significantly reduce the carriage and shedding of *E. coli* O157 and *Salmonella enterica*.[131] Shedding of *E. coli* O157:H7 was reduced in cattle after the dietary inclusion of a multi-strain probiotic containing *L. acidophilus* and *P. freudenreichii*.[129] Strains of LAB are most effective in reducing the carriage of gut pathogens in ruminants.[128] Incidences of diarrhoea and other diseases of the GIT that result in weight loss in young ruminants (especially lambs and calves) have been shown to subside after the application of LAB.[30,64,132] Stress in ruminants may cause an imbalance in the gut microflora or dysbiosis, which may be controlled through the administration of probiotics.[2] The application of dietary probiotics in livestock production not only reduces pathogen carriage and gut disease, but also further limits the risk of human infections with foodborne pathogens.[130]

Haemato-biochemical parameters and metabolites

There are conflicting reports on the effects of probiotics on haemato-biochemical parameters and metabolites levels in ruminants. Although some studies show no difference in glucose concentration in lambs supplemented with probiotic,[51,133] Antunović *et al.*[134] and Bruno *et al.*[135] reported significant decreases in glucose concentrations. Conversely, probiotic supplementation of lactating ewes and lambs significantly increased the concentration of glucose.[126,136] It was reported previously that the relationship existing between blood glucose levels and probiotic inclusion is dose-dependent.[137] Cetin *et al.*[138] observed a statistical increase in erythrocyte sedimentation rate, haemoglobin concentration and haematocrit values in animals supplemented with probiotics. The supplementation of either single strains of *L. lactis* and *L. plantarum* or their combination as multi-strain probiotics significantly increased total red blood cell counts and haemoglobin concentration in the blood.[139] The dietary inclusion of probiotics positively influenced haematopoiesis, which, amongst others, benefits increases in total white blood cell counts, hence enhancing immune cells synthesis, further protecting the host against invading pathogens.[1,140]

The findings from several studies revealed that supplementation with probiotics in animals may significantly improve the lipid profile in the blood of ruminants.[141] The supplementation of kids or lambs with probiotics was shown to decrease the concentrations of triglycerides, total lipids, low-density lipoproteins and non-esterified fatty acids in the blood of ruminants.[142,143] Panda *et al.*[144] reported a significant reduction in total cholesterol and triglycerides by dietary inclusion of 100 mg kg^{-1} diet of *Lactobacillus sporogenes* probiotic in animals. Total cholesterol reduction in probiotic supplemented animals could be the result of direct assimilation of cholesterol by bacterial cells (which causes a reduction in the cholesterol absorption and synthesis in the GIT), 3-hydroxy-3-methyl-glutaryl-CoA reductase inhibition and bile salt hydrolysis.[145,146] Furthermore, triglyceride reduction in probiotic treated animals may be a result of increased hydrolysis of bile salts, which causes inadequate lipid absorption in the small intestine.[147] Strains of *Lactobacillus* are known to show high hydrolytic activity of bile salts, which consequently leads to bile salt deconjugation within the GIT.[148] Several studies have reported a decrease in the concentration of certain blood metabolites including urea and blood urea nitrogen when lambs were fed with diets supplemented with probiotics.[134135,] Probiotic supplementation in lambs increases the bacterial population in the rumen, which may lead to improved utilization of nitrogen by ruminal bacteria thereby reducing blood urea nitrogen concentration[135] (Table 2).

SUSTAINABILITY OF RUMINANT PRODUCTION

The importance of ruminants in the production of high volumes of meat and milk, which are important animal proteins for human nutrition and health, and their ability to effectively use fibrous non-digestible feed cannot be overemphasized.[6] Despite an increasing loss in soil fertility, desertification, erosion and drought, the vast majority of people in the developing world primarily depend on ruminants as their major food sources.[149] However, apart from this, the environmental impact of the emission of greenhouse gases by ruminants and other problems associated with their health and welfare constitutes a major global challenge.[7]

With the continued global rise in the human population, the supply of sufficient, high quality and safe food is threatened by a myriad of factors.[150] Food security and the sustainability of agriculture, especially livestock production, has become an immense concern for both developed and developing countries of the world.[2] Considering the role that ruminants play both in the production of human food and employment, there is an urgent need to chart a new course of action that will lead to a sustainable increase in the production of food of ruminant origin, as well as improve the health and welfare of animals.[6,151]

The increased interest in organic farming and consumers' preference for chemical and/or antibiotic-free animal products will lead to more sustainable and beneficial effects both in the livestock industry, as well as environmental and public health. Furthermore, the inclusion of probiotics and other natural, safe and novel feed sources in animal husbandry may lead to a significant improvement in the production of food which will also be more sustainable.[152] Although plant- and cell-based food are becoming more prevalent in human diets, ruminants are able to transform plant material that is undigestible by humans into animal foods of high nutritive value. If there is no global advancement for alternatives to the use of antibiotics in ruminant-based food production systems, negative impacts on their productivity could occur, leading to shortages in food production.[149] Advantages from the use of probiotics could extend to systems that do not rely on the use of antibiotics, such as organic farming. Should the current trend in human population increase continue, by 2050, there will be less arable land, which will eventually create unhealthy competition, overexploitation and a decline in biodiversity. As such, an improvement and intensification of sustainable agriculture and livestock production will be the only realistic solution to meet human needs.[149] The global acceptance of sustainable ruminant production through supplementation with probiotics may thus help maintain food security and food safety for the world.

FUTURE DIRECTION AND CONCLUSIONS

The supplementation of ruminants with probiotics can contribute immensely to improved growth, general performance and overall health status. However, continuous in-depth, comprehensive and encompassing *in vivo* studies that use high-throughput omic technologies to fully decipher the mechanisms and effects exerted by probiotics on ruminants and their role in improving animal health and nutrition, as well as the subsequent effect on the sustainability of food production, are needed. Also, the characterization of metabolites secreted by probiotic strains and their role in improving ruminants' health and nutrition should be explored.

ACKNOWLEDGEMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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