

Review

Recent trends in the use of *Bacillus* species as probiotics in animal production: an overview

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Abstract: The increasing prevalence of antimicrobial resistance (AMR), growing concerns regarding antimicrobial residues, and restrictions on the use of antibiotic growth promoters have intensified the search for safe and sustainable alternatives in animal production. Among the diverse probiotic microorganisms investigated for this purpose, *Bacillus* species have attracted particular attention because of their endospore-forming capacity, resistance to processing and gastrointestinal stresses, and broad range of functional activities. This review summarizes recent trends in the application of *Bacillus*-based probiotics across animal production systems, with emphasis on their mechanisms of action, functional benefits, technological advances, challenges, and future prospects. Species including *Bacillus subtilis*, *B. licheniformis*, *B. amyloliquefaciens*, *B. coagulans*, and *B. clausii* have been investigated in poultry, swine, ruminants, aquaculture, insects, and companion animals, with reported effects on intestinal microbial homeostasis, nutrient digestion and utilization, immune modulation, pathogen suppression, intestinal barrier integrity, and production performance. Recent advances in genomics, metagenomics, microbiome research, synbiotic formulations, encapsulation technologies, and precision livestock farming are expanding opportunities for strain-specific selection and targeted probiotic application. Evidence from experimental and production studies indicates that appropriately selected *Bacillus* strains can improve growth performance, feed efficiency, nutrient utilization, disease resistance, and selected environmental outcomes while potentially reducing dependence on conventional antimicrobial interventions. Nevertheless, substantial challenges remain, particularly regarding strain-specific efficacy, safety and genomic characterization, consistency under commercial conditions, formulation, dose optimization, and regulatory harmonization. Overall, *Bacillus*-based probiotics represent a promising multifunctional approach for supporting animal health and productivity and contributing to more sustainable and antimicrobial-responsible animal production systems.

Keywords: *Bacillus* spp.; probiotics; animal production; gut health; antimicrobial resistance

1. Introduction

The rapidly increasing global demand for animal-derived foods has accelerated the intensification and commercialization of livestock, poultry, and aquaculture production systems. Intensification is essential for meeting the nutritional and economic demands of a growing population; however, it also increases the risk of infectious diseases, production losses, and disruptions of animal health when biosecurity, nutrition, and health-management practices are inadequate (Henchion *et al.*, 2021). In developing production systems, particularly small- and medium-scale farms, limitations in farm management, disease prevention, and implementation of good production practices can further increase the dependence on antimicrobial agents. Studies from Bangladesh, for example, have documented considerable variation in poultry production systems and highlighted the importance of appropriate health-management and farm-level practices for maintaining productivity and food safety (Mohanta *et al.*, 2015; Akhter *et al.*, 2018; Ali *et al.*, 2019). The occurrence of diverse poultry diseases under intensive production conditions further complicates disease management and can encourage inappropriate antimicrobial use (Hassan *et al.*, 2016).

Antimicrobial agents have historically played an important role in the prevention and treatment of infectious diseases and, in some production systems, have been used to improve production efficiency. However, inappropriate, excessive, and prolonged antimicrobial use has contributed to the emergence and dissemination of antimicrobial-resistant microorganisms. Antimicrobial resistance (AMR) is now recognized as a major One Health challenge because resistant microorganisms and resistance determinants can circulate among animals, humans, food, and the environment. The extensive use of antibiotics in animal production therefore has implications that extend beyond farm-level productivity to food safety, public health, and environmental health (Kabir, 2009a; Hosain *et al.*, 2022; Kabir, 2026a). In Bangladesh, concerns regarding antibiotic use, antimicrobial residues, and the development of resistance in the poultry sector have further emphasized the need for stronger antimicrobial stewardship and sustainable alternatives to antibiotic-dependent production practices (Rahman *et al.*, 2016; Islam, 2025). Consequently, reducing unnecessary antimicrobial exposure while maintaining animal health and productivity has become an important component of contemporary livestock and poultry production strategies (Rashid *et al.*, 2016; Islam, 2026).

The increasing global emphasis on antimicrobial stewardship has stimulated substantial interest in nutritional and microbial interventions capable of improving animal health without relying primarily on conventional antibiotics (Arif *et al.*, 2021). Probiotics represent one of the most extensively investigated alternatives. They are generally defined as live microorganisms that, when administered in adequate amounts, confer a health benefit on the host (Arsène *et al.*, 2021). Probiotic microorganisms can influence gastrointestinal microbial communities, nutrient digestion, intestinal barrier function, immune responses, and resistance to pathogenic microorganisms. The potential of probiotics is not restricted to a single microbial group; strains belonging to *Lactobacillus*, *Bifidobacterium*, *Bacillus*, and other genera have been investigated for applications in animal production. Previous studies have demonstrated the importance of systematic isolation and characterization of probiotic microorganisms, including evaluation of their antimicrobial activity and other functional properties (Kabir *et al.*, 2016; Hossain *et al.*, 2018).

Among the diverse microorganisms investigated as probiotics, species of the genus *Bacillus* have received particular attention because of their distinctive capacity to form highly resistant endospores. Unlike many non-spore-forming probiotic microorganisms, *Bacillus* spores can tolerate adverse environmental conditions, including dehydration, variations in pH, oxygen exposure, and relatively high temperatures encountered during feed manufacturing and storage (Elshaghabe *et al.*, 2017; Mingmongkolchai and Panbangred, 2018). This property provides an important technological advantage for their incorporation into commercial feed, premixes, and other feed-based delivery systems. Following ingestion, spores can survive passage through the upper gastrointestinal tract and may germinate under suitable conditions, allowing the resulting vegetative cells to interact with the intestinal environment (Todorov *et al.*, 2022).

Several *Bacillus* species, including *Bacillus subtilis*, *B. licheniformis*, *B. amyloliquefaciens*, *B. coagulans*, and *B. clausii*, have been extensively investigated for their potential benefits in animal production. Their effects are not attributable to a single mechanism. Depending on the strain and host, *Bacillus* probiotics may produce extracellular digestive enzymes, antimicrobial compounds, bacteriocins, and bioactive lipopeptides; compete with pathogenic microorganisms for nutrients and adhesion sites; influence intestinal microbial communities; and stimulate components of innate and adaptive immunity. These activities can contribute to improved gastrointestinal homeostasis, nutrient utilization, intestinal barrier function, and resistance to selected pathogens (Elshaghabe *et al.*, 2017; Grant *et al.*, 2018; Tang *et al.*, 2024). The production of enzymes such as proteases, amylases, and lipases is particularly relevant to animal nutrition because supplementation may complement endogenous digestive processes and improve the availability of nutrients from complex feed ingredients.

The application potential of *Bacillus*-based probiotics extends across major animal production sectors. In poultry, supplementation has been investigated for improving growth performance, feed efficiency, intestinal health, and resistance to enteric pathogens. This is particularly relevant because poultry production systems are frequently challenged by infectious diseases and high production pressure, creating a need for nutritional strategies that can support health while reducing unnecessary antimicrobial exposure (Hassan *et al.*, 2016; Akhter *et al.*, 2018). In swine, *Bacillus* probiotics have been associated with improved growth performance, intestinal morphology, microbial balance, and reduced gastrointestinal disturbances, particularly during the vulnerable post-weaning period. In ruminants, probiotic supplementation has been explored for its potential effects on ruminal fermentation, fiber digestion, animal productivity, and environmental performance. In aquaculture, probiotics are increasingly considered important components of health-management strategies because manipulation of the microbial environment can contribute to disease control, nutrient utilization, and production sustainability (Shahjahan, 2024).

The importance of probiotic-based strategies is further strengthened by their potential contribution to food safety and One Health (Atasever, 2026). Veterinary health management is closely connected with the safety of animal-derived foods and the prevention of hazards that can move across animal, human, and environmental interfaces (Atasever, 2025). Reducing unnecessary antimicrobial use through effective nutritional and microbial interventions may help decrease antimicrobial selection pressure and the potential occurrence of antimicrobial residues, while maintaining animal productivity. More broadly, food safety requires multidisciplinary approaches integrating animal health, production practices, environmental management, and public-health considerations (Nasirujjaman, 2024).

Recent advances in probiotic technology have also expanded the potential applications of *Bacillus* species. Modern approaches involving genomics, metagenomics, bioinformatics, and microbiome analysis are facilitating more detailed characterization of probiotic strains and their functional attributes. These technologies can help identify genes associated with antimicrobial activity, enzyme production, stress tolerance, host interaction, and other desirable phenotypes, thereby supporting more rational strain selection (Grant *et al.*, 2018). At the formulation level, microencapsulation and related delivery technologies are being investigated to protect probiotic microorganisms during processing, storage, and gastrointestinal transit. Recent work on the microencapsulation of locally isolated probiotic strains illustrates the increasing importance of delivery technology in maintaining probiotic viability and functional activity (Jalil *et al.*, 2025). Despite these advantages, the efficacy of *Bacillus* probiotics is not universal. Probiotic effects are highly strain-specific and may vary according to animal species, age, diet, production system, dosage, formulation, gastrointestinal microbiota, and health status. A strain that performs effectively under controlled experimental conditions may not necessarily produce equivalent outcomes under commercial farming conditions. Furthermore, the presence of potentially undesirable genes, AMR determinants, or virulence-associated characteristics in some *Bacillus* strains highlights the need for comprehensive genomic and phenotypic safety assessment before widespread application. Standardization of strain identification, dose, efficacy assessment, safety evaluation, and regulatory requirements remains essential for translating experimental findings into reliable commercial products (Mingmongkolchai and Panbangred, 2018).

These challenges highlight the need to move beyond the general identification of probiotic microorganisms toward strain-specific understanding of *Bacillus*–host–microbiome interactions, supported by advances in functional characterization, microbiome science, formulation technologies, precision livestock farming, and One Health approaches. Such integration is particularly relevant under changing climatic conditions that may influence animal health, productivity, and food safety (Kabir, 2026b). Against this background, this review provides an updated overview of *Bacillus* species and strains used as probiotics across animal-production systems, with emphasis on their mechanisms of action, effects on growth, feed utilization, intestinal health, immunity and disease resistance, recent advances in strain selection and delivery technologies, and contributions to sustainable production and antimicrobial stewardship. It also critically examines current limitations related to strain specificity, safety, efficacy, regulatory requirements, and commercial implementation, thereby highlighting the future potential of *Bacillus*-based probiotics as multifunctional tools for improving animal health, productivity, food safety, and environmental sustainability while reducing dependence on conventional antimicrobial interventions.

2. An overview of probiotic *Bacillus* species

The genus *Bacillus* comprises a diverse group of predominantly Gram-positive, rod-shaped bacteria belonging to the family Bacillaceae within the phylum Bacillota. Members of the genus are characterized by their ability to produce highly resistant endospores, although considerable physiological, biochemical, and genomic diversity

exists among species and strains (Schallmeyer *et al.*, 2004; de Blackburn and McClure, 2009). The ability to form endospores is particularly important from a probiotic perspective because spores can withstand environmental stresses such as heat, dehydration, fluctuations in pH, and prolonged storage. Consequently, *Bacillus* species can be incorporated into feed and subjected to processing conditions that may compromise the viability of many non-spore-forming probiotic microorganisms. Members of the genus are widely distributed in soil, water, plants, food, and animal-associated environments and have diverse applications in agriculture, biotechnology, medicine, and food production (Schallmeyer *et al.*, 2004).

The probiotic potential of *Bacillus* is largely associated with a combination of technological stability and biological functionality. Several species and strains have demonstrated the ability to survive gastrointestinal transit, germinate under favorable intestinal conditions, produce digestive enzymes and antimicrobial metabolites, interact with the resident microbiota, and modulate host immune responses. These characteristics have stimulated considerable interest in *Bacillus* as a feed-based probiotic for improving intestinal health, nutrient utilization, growth performance, and disease resistance in food-producing animals (Ramlucken *et al.*, 2020). Importantly, probiotic activity is highly strain-dependent; therefore, the demonstrated efficacy of one *Bacillus* strain cannot necessarily be extrapolated to other strains of the same species.

Several *Bacillus* species have been investigated extensively as probiotics in poultry, swine, ruminants, and aquaculture. Among them, *B. subtilis*, *B. licheniformis*, *B. amyloliquefaciens*, *B. coagulans*, and *B. clausii* have received particular attention because of their documented functional properties and suitability for feed supplementation. Representative species and strains, together with their reported probiotic functions and target animal species, are summarized in Table 1.

Table 1. Notable species of the *Bacillus* genus used as probiotics in animal production.

Bacillus species/ strain	Primary probiotic functions	Target animal species	References
<i>Bacillus subtilis</i> natto	Enhances gut health, produces antimicrobials (subtilin), improves feed conversion ratio (FCR)	Poultry, swine, ruminants	Stein (2005); Liu <i>et al.</i> (2025)
<i>B. subtilis</i> PB6	Improves growth performance and immune function	Weaned piglets	Liu <i>et al.</i> (2025)
<i>B. subtilis</i> B-2998D	Developes a balanced intestinal microbiota and boosts immunity	Sheep and lambs	Devyatkin <i>et al.</i> (2021)
<i>B. subtilis</i> B-3057D	Develops a balanced gut health, increase absorption and boosts immunity	Sheep and lambs	Devyatkin <i>et al.</i> (2021)
<i>B. licheniformis</i> B-2999D	Developing a balanced intestinal microbiota and improves digestibility	Sheep and lambs	Devyatkin <i>et al.</i> (2021)
<i>B. licheniformis</i>	Increase in feed consumption, decreases weight loss during the suckling period.	Sows	Alexopoulos <i>et al.</i> (2004)
<i>B. subtilis</i> spores	Lowers the proportion of Mastitis-Metritis-Agalactia (MMA), improve the health status and fertility	Sows	Alexopoulos <i>et al.</i> (2004)
<i>B. subtilis</i> C-3102	Improves growth performance and feed efficiency	Poultry	Jeong and Kim (2014)
<i>B. coagulans</i>	Balances the intestinal microbiota, promotes metabolism and utilization of nutrients, improves immunity	Ruminants	Zhou <i>et al.</i> (2020)
<i>B. coagulans</i>	Increases growth performance, improves feed intake, enhances gut mucosa and immune organs, and regulates immunity	Poultry	Elleithy <i>et al.</i> (2023)

The functional benefits of *Bacillus* probiotics arise from several complementary mechanisms. Following ingestion, *Bacillus* spores can survive passage through the upper gastrointestinal tract and, under suitable conditions, germinate and interact with the intestinal environment (Kabir *et al.*, 2004; Kabir *et al.*, 2005). Vegetative cells can produce extracellular enzymes, including proteases, amylases, and lipases, which may complement endogenous digestive processes and improve the degradation and utilization of dietary nutrients (Grant *et al.*, 2018; Ramirez-Olea *et al.*, 2022). Consequently, supplementation with selected *Bacillus* strains

has been associated with improved feed efficiency, nutrient absorption, and growth performance in different animal production systems.

Another important characteristic of probiotic *Bacillus* species is their ability to produce diverse antimicrobial metabolites. These include bacteriocins, lipopeptides, and other bioactive compounds that can inhibit pathogenic or opportunistic microorganisms and contribute to the maintenance of intestinal microbial homeostasis. Such activities may reduce the intestinal burden of pathogens and support a more favorable microbial environment (Grant *et al.*, 2018). In contrast to some lactic acid bacteria, for which lactic acid production is a prominent antimicrobial mechanism, the probiotic activity of *Bacillus* is more appropriately associated with spore-mediated persistence, antimicrobial metabolite production, enzyme secretion, competitive interactions with pathogens, and modulation of host responses.

Evidence also indicates that selected *Bacillus* strains can influence host immune function. Their interaction with the gastrointestinal environment may stimulate innate and adaptive immune responses and contribute to improved resistance against infectious challenges (Liang *et al.*, 2024). These effects are particularly relevant in young and intensively managed animals, in which gastrointestinal disturbances and infectious diseases can adversely affect productivity. Accordingly, *Bacillus*-based probiotics have been investigated extensively in poultry, swine, ruminants, and aquaculture as nutritional interventions for supporting gut health and improving production performance.

The diversity of the genus also warrants careful consideration of safety. Although several *Bacillus* species have well-established histories of beneficial use, the genus contains both beneficial and potentially pathogenic members (Schallmeyer *et al.*, 2004). In particular, *B. cereus* is recognized as an opportunistic pathogen and foodborne hazard; therefore, any consideration of *B. cereus* as a probiotic must be restricted to rigorously characterized strains with demonstrated safety and absence of relevant virulence and toxin-associated determinants. Reports describing probiotic potential among selected *B. cereus* strains should therefore not be generalized to the species as a whole (Albahri and Jessberger, 2026).

Beyond terrestrial livestock, *Bacillus* probiotics have considerable potential in poultry and aquaculture, where they have been investigated for improving feed utilization, growth, intestinal microbial balance, and disease resistance (Tang *et al.*, 2018). Probiotic applications in aquaculture are particularly relevant because manipulation of the microbial environment can contribute to host health while potentially reducing reliance on antimicrobial treatments (Kim *et al.*, 2020; Shahjahan, 2024). Similarly, broader probiotic research has demonstrated the importance of selecting strains with specific functional properties and developing appropriate delivery systems to maintain viability and activity throughout processing and administration (Kabir *et al.*, 2016; Hossain *et al.*, 2018; Jalil *et al.*, 2025).

3. Mechanisms of action of *Bacillus* as probiotics

The probiotic effects of *Bacillus* strains are mediated through multiple complementary mechanisms that collectively contribute to gastrointestinal health, physiological adaptation, disease resistance, and overall animal performance (Amoah *et al.*, 2023). One of the major advantages of *Bacillus* species is their ability to form highly resistant endospores. This characteristic enables them to withstand adverse environmental conditions, including the low pH of the stomach and the elevated temperatures encountered during feed processing, thereby increasing the likelihood that viable spores reach the intestinal tract (Mingmongkolchai and Panbangred, 2018). Following gastrointestinal transit, spores can germinate under suitable conditions and interact with the intestinal environment, where they may exert several beneficial effects.

Competitive exclusion is considered an important mechanism by which *Bacillus* probiotics contribute to pathogen control (Zhao *et al.*, 2024). *Bacillus* strains can compete with pathogenic microorganisms for nutrients, ecological niches, and adhesion sites within the gastrointestinal tract, thereby limiting pathogen colonization and proliferation (Piewngam *et al.*, 2018). In addition, certain *Bacillus* strains can interfere with bacterial communication systems, including quorum sensing, which may reduce the expression of virulence-associated factors and consequently impair pathogen establishment and pathogenicity (Davares *et al.*, 2022). These interactions can contribute to the maintenance of intestinal microbial homeostasis and reduce the likelihood of enteric infections.

The production of antimicrobial compounds represents another important mechanism underlying the probiotic activity of *Bacillus*. Different species and strains can produce a diverse array of bioactive metabolites, including bacteriocins, lipopeptides such as surfactin, iturin, and fengycin, and other antimicrobial substances with activity against pathogenic microorganisms, including *Salmonella*, *Escherichia coli*, and *Clostridium* spp. (Zhang *et al.*, 2024). The major antimicrobial compounds reported from probiotic *Bacillus* species and their principal functions are summarized in Table 2.

Table 2. Key antimicrobial agents produced by probiotic *Bacillus* species.

<i>Bcillus</i> species	Potential antimicrobial agent	Functions	References
<i>Bacillus subtilis</i>	Subtilin, Iturin A, Surfactin, Fengycin	Inhibits <i>Clostridium perfringens</i> , <i>E. coli</i> , <i>Salmonella</i> spp.; promotes gut health	Stein (2005)
<i>B. amyloliquefaciens</i>	Bacillomycin D, Surfactin, Fengycin, Iturin A	Antifungal, antibacterial; protects against <i>Salmonella</i> and promotes gut microbiota balance	Chen <i>et al.</i> (2007)
<i>B. licheniformis</i>	Lichenicidin, Bacitracin, Lichenysin	Broad-spectrum antibacterial; inhibits <i>Staphylococcus</i> spp. and <i>Clostridium</i> spp.	Shleeva <i>et al.</i> (2023)
<i>B. pumilus</i>	Pumilacidin, Bacilysin	Antibacterial and anti-inflammatory effects; modulates gut microbiota	Naruse <i>et al.</i> (1990)
<i>B. cereus</i> (non-pathogenic strains)	Cerein, Bacillibactin	Effective against Gram-positive bacteria; iron chelation inhibits pathogenic growth	Jensen <i>et al.</i> (2001)
<i>B. megaterium</i>	Megacin, Bacillibactin	Supports immune response; shows antibacterial activity in animal gut	Laptev (2020)
<i>B. coagulans</i>	Coagulin	Inhibits <i>Salmonella</i> , <i>Listeria</i> , <i>Clostridium</i> spp.; stabilizes intestinal flora	Zhou <i>et al.</i> (2020)
<i>B. velezensis</i>	Iturin A, Bacillomycin D, Surfactin, Fengycin	Strong antifungal and antibacterial activity; effective in poultry and swine gut health	Ye <i>et al.</i> (2020)
<i>B. thuringiensis</i>	Thuringiensin, Cytotoxins (used with care in non-insecticidal strains)	Potential use in parasite and protozoan control; limited use due to toxin concerns	Rea <i>et al.</i> (2010)
<i>B. clausii</i>	Clausin, bacteriocins	Broad-spectrum antimicrobial activity; commonly used in veterinary probiotics	Ghelardi <i>et al.</i> (2022)

The antimicrobial activity of *Bacillus* probiotics can help maintain intestinal microbial homeostasis and may reduce the need for conventional antimicrobial interventions. In addition to pathogen suppression, *Bacillus* species contribute to digestive processes through the production of extracellular enzymes. Selected strains can secrete amylases, proteases, lipases, and cellulases, which complement endogenous digestive enzymes and facilitate the degradation and assimilation of dietary nutrients (Lippolis *et al.*, 2013; Gong *et al.*, 2018). Improved digestion and nutrient utilization may consequently contribute to enhanced feed efficiency and growth performance.

Immune modulation represents another important component of the probiotic activity of *Bacillus*. Interactions between *Bacillus* strains and the gut-associated lymphoid tissue (GALT) can influence both innate and adaptive immune responses (Rhee *et al.*, 2004). These interactions may promote immunoglobulin production, including secretory IgA, and stimulate the activity of immune cells such as macrophages and dendritic cells, as well as modulate cytokine production (Vieco-Saiz *et al.*, 2025). Through these effects, *Bacillus* probiotics may strengthen mucosal defense mechanisms and improve the host's ability to respond to enteric pathogens.

Maintenance of intestinal barrier integrity is also an important mechanism through which *Bacillus* probiotics may support host health. Certain strains can influence the expression and function of tight-junction proteins, thereby helping to maintain epithelial barrier integrity and limiting excessive intestinal permeability and the translocation of pathogens or harmful microbial products across the intestinal epithelium (Ferris *et al.*, 2025; Mercado-Monroy *et al.*, 2026). Preservation of intestinal barrier function is particularly important because disruption of epithelial integrity can increase exposure to microbial antigens and contribute to intestinal inflammation and impaired animal performance.

Emerging evidence further suggests that some *Bacillus* strains can influence host metabolic and inflammatory pathways and modulate the expression of genes associated with growth, stress tolerance, and inflammatory responses (Lu *et al.*, 2024). These effects may be particularly relevant during physiologically challenging periods, including weaning, transportation, and exposure to heat stress, when disruption of intestinal and systemic homeostasis can negatively affect animal health and productivity (Lu *et al.*, 2024). The combined

action of these mechanisms provides a biological basis for the potential of *Bacillus*-based probiotics to improve gastrointestinal health, nutrient utilization, disease resistance, and overall productivity in animal production systems. The overall mechanisms of action of *Bacillus* probiotics are illustrated in Figure 1.

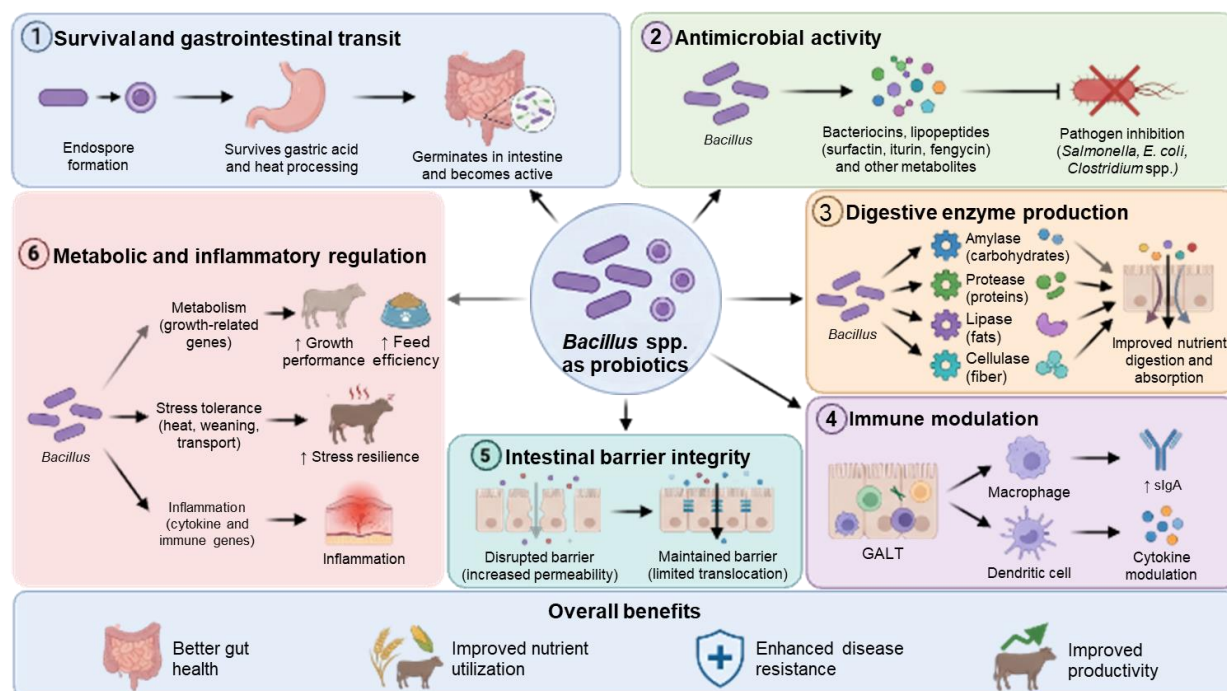


Figure 1. Mode of action of *Bacillus* spp. as probiotics.

4. Benefits of *Bacillus* probiotics in animal production

The application of *Bacillus*-based probiotics in animal production has gained increasing attention as a potential alternative or complementary strategy to antibiotic growth promoters, particularly in the context of antimicrobial stewardship and sustainable livestock production (Luise *et al.*, 2022). The distinctive ability of *Bacillus* species to form highly resistant endospores provides an important technological advantage over many non-spore-forming probiotics. These spores can tolerate adverse conditions encountered during feed manufacture, storage, and gastrointestinal transit, including elevated processing temperatures, dehydration, and acidic conditions in the stomach (Mingmongkolchai and Panbangred, 2018). This stability facilitates their incorporation into commercial feed formulations while maintaining probiotic viability and functional potential. Consequently, *Bacillus* probiotics can provide a combination of technological and biological benefits that contribute to animal health, productivity, and environmental sustainability (Rosenstrauch, 2018).

One of the principal benefits of *Bacillus* probiotics is the improvement of intestinal microbial homeostasis. Species such as *B. subtilis*, *B. licheniformis*, and *B. coagulans* can interact with the gastrointestinal microbiota and contribute to a more favorable intestinal microbial environment (Grant *et al.*, 2018). Their beneficial effects are associated with several complementary activities, including competition with pathogenic microorganisms for nutrients and adhesion sites and the production of antimicrobial metabolites such as bacteriocins and lipopeptides. By limiting the establishment and proliferation of undesirable microorganisms, *Bacillus* probiotics may contribute to improved intestinal health and reduced incidence of enteric disturbances. Maintenance of a stable intestinal microbial community is also closely associated with efficient digestion, nutrient absorption, and optimal physiological function.

Improved digestive capacity and nutrient utilization represent another important benefit of *Bacillus* supplementation. Selected *Bacillus* strains produce extracellular enzymes, including amylases, proteases, and lipases, which facilitate the degradation of complex dietary components and complement endogenous digestive processes (Gong *et al.*, 2018). Enhanced digestion and nutrient availability may subsequently improve feed utilization and feed conversion ratio (FCR), thereby supporting growth and production performance. Such effects have been reported particularly in poultry, swine, and aquaculture systems, although the magnitude of the response can vary according to the probiotic strain, dose, animal species, production stage, and dietary composition (Zhu *et al.*, 2023).

Modulation of host immunity is another important functional attribute of *Bacillus* probiotics. Supplementation can influence both innate and adaptive immune responses, potentially enhancing the capacity of animals to resist infectious challenges (Roy *et al.*, 2015). In addition, some *Bacillus* strains have been associated with reductions in intestinal oxidative stress and inflammatory responses, which may help maintain physiological homeostasis and reduce the metabolic costs associated with persistent immune activation (Tang *et al.*, 2019). By supporting intestinal integrity and regulating inflammatory processes, probiotics may contribute to improved animal health and more efficient allocation of nutrients toward growth and production rather than defense against chronic intestinal disturbances.

The benefits of *Bacillus* probiotics may extend beyond individual animal health to broader environmental outcomes. Improved nutrient digestion and utilization can potentially reduce the quantity of undigested nutrients excreted into the environment. In some production systems, probiotic supplementation has also been associated with reductions in emissions of undesirable gases, including ammonia and methane, although these effects are dependent on animal species, diet, management practices, and probiotic characteristics (El Bied *et al.*, 2024). Such effects are particularly relevant to sustainable animal production because improved nutrient-use efficiency can reduce nutrient losses and contribute to lowering the environmental footprint of intensive production systems.

The spore-forming nature of *Bacillus* species also provides important commercial advantages. Compared with many vegetative probiotic microorganisms, *Bacillus* spores generally exhibit greater stability during feed processing, storage, and transportation, potentially providing longer shelf life and facilitating incorporation into commercial feed products (Mingmongkolchai and Panbangred, 2018). This technological robustness can improve the practicality of large-scale probiotic application, particularly where feed is exposed to elevated temperatures or prolonged storage conditions. Furthermore, the potential of *Bacillus* probiotics to suppress important enteric pathogens, including *Salmonella* and *E. coli*, is relevant to animal health, food safety, and the reduction of pathogen transmission through the food-production chain.

Collectively, these characteristics demonstrate that *Bacillus* probiotics can provide multiple and interconnected benefits in animal production. Their ability to withstand feed-processing and gastrointestinal stresses, regulate intestinal microbial communities, enhance digestive and nutrient-utilization processes, modulate immune responses, support intestinal health, and potentially improve environmental performance makes them attractive components of modern animal production strategies (Luise *et al.*, 2022). However, the magnitude and consistency of these benefits are not uniform across all *Bacillus* strains or production systems. Therefore, the selection of well-characterized strains and appropriate supplementation strategies remains essential for translating their demonstrated biological potential into consistent improvements in animal health, productivity, welfare, and sustainability.

5. Application of *Bacillus* probiotics across animal production systems

Bacillus-based probiotics are increasingly used across diverse animal production systems because of their potential to improve intestinal health, immune function, nutrient utilization, and growth performance (Grant *et al.*, 2018). Their ability to form resistant endospores provides considerable advantages during feed processing, storage, and gastrointestinal transit, making them suitable for incorporation into animal feed (Todorov *et al.*, 2022). However, their effects vary according to the *Bacillus* strain, animal species, production stage, and management conditions.

In poultry, *Bacillus subtilis* and *B. licheniformis* are among the most extensively investigated species, particularly for improving feed efficiency and controlling enteric pathogens (Xu *et al.*, 2021). Supplementation can modulate intestinal microbiota, enhance nutrient utilization, and reduce the incidence or severity of enteric disorders such as necrotic enteritis associated with *Clostridium perfringens* (Wang *et al.*, 2021a). Probiotic supplementation has also been associated with improvements in poultry meat quality, indicating that the benefits may extend beyond growth and intestinal health (Kabir, 2009b).

In swine production, *Bacillus* supplementation has been associated with improved growth performance, feed conversion, and reduced diarrhea, particularly in weaned piglets (Tian *et al.*, 2021). These effects have been linked to improvements in intestinal morphology, immunomodulation, and suppression of pathogenic microorganisms (Li *et al.*, 2021). In addition, the production of extracellular enzymes, including proteases and amylases, may enhance feed digestion and nutrient utilization (Contesini *et al.*, 2018).

In ruminants, *Bacillus* probiotics have been investigated for their effects on ruminal microbial stability, fiber digestion, animal growth, and environmental performance. Supplementation may improve ruminal function and fiber utilization while contributing to reduced methane emissions (Chaucheyras-Durand and Fonty, 2002; Saleem *et al.*, 2025). In aquaculture, *Bacillus* species are widely explored as probiotics because of their ability

to improve microbial water quality, enhance host disease resistance, and support the health and performance of cultured species such as tilapia and shrimp (Zokaeifar *et al.*, 2012). Collectively, these applications indicate that *Bacillus* probiotics can serve as a versatile alternative or complementary approach to conventional antimicrobial interventions for improving animal health, productivity, and production efficiency (Arsène *et al.*, 2021). Figure 2 provides a schematic overview of the major application areas and functional benefits of *Bacillus* probiotics across poultry, swine, ruminants, aquaculture, insects, and companion animals. Their reported benefits include improved growth performance, gut health, nutrient utilization, feed efficiency, immune modulation, and pathogen suppression. Depending on the production system, *Bacillus* probiotics may also contribute to improved egg and milk production, reduced methane emissions in ruminants, improved water quality in aquaculture, enhanced larval growth in insects, and improved intestinal and immune health in companion animals.

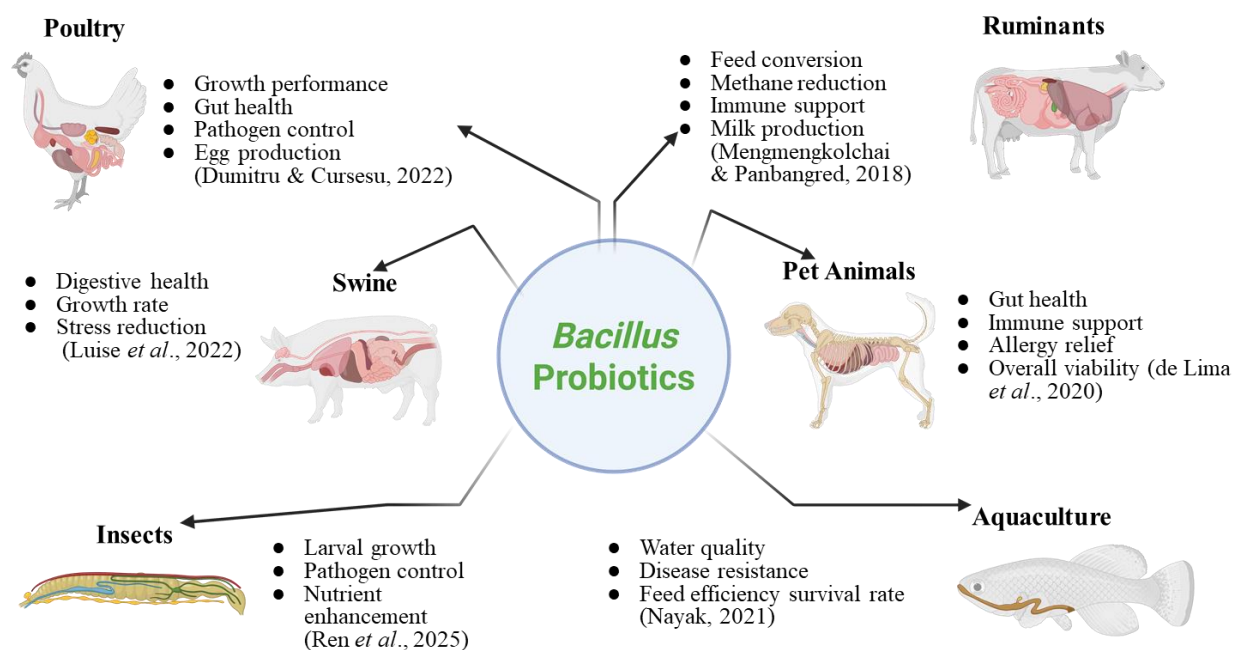


Figure 2. Contribution of *Bacillus* probiotics to sustainable animal production.

6. Challenges and limitations

Despite the considerable potential of *Bacillus* species as probiotics, several challenges limit their consistent application across animal production systems. Their spore-forming capacity and tolerance to environmental stress provide important technological advantages, but these characteristics alone do not guarantee probiotic efficacy *in vivo* (Elshaghabee *et al.*, 2017). One of the major limitations is pronounced strain-to-strain variability. Different *Bacillus* strains can differ substantially in their ability to survive gastrointestinal transit, germinate, colonize or interact with the intestinal environment, produce functional metabolites, and modulate host responses. Consequently, not all strains within a given species exhibit measurable probiotic effects under *in vivo* conditions (Cutting, 2011). Rigorous strain-level screening, characterization, and validation are therefore essential before commercial application.

The efficacy of *Bacillus* probiotics can also vary considerably according to animal species, age, diet, production system, environmental conditions, and physiological status (Elshaghabee *et al.*, 2017). Interactions with the resident gut microbiota, host immune status, and dietary composition may influence the establishment and functional activity of supplemented strains (Grant *et al.*, 2018). Moreover, probiotic supplementation may occasionally alter hematological and biochemical parameters, highlighting the importance of evaluating physiological responses and safety rather than relying solely on growth-performance indicators (Islam *et al.*, 2004). Although *Bacillus* spores generally remain stable during feed processing and storage, their subsequent germination and functional activity within the gastrointestinal tract are not always predictable. This limitation may be particularly relevant in poultry and other animals with relatively rapid gastrointestinal transit, where insufficient time may be available for germination and establishment of biological activity (Bernardeau *et al.*, 2017).

Safety assessment represents another critical consideration. The genus *Bacillus* includes both beneficial and potentially pathogenic or toxigenic members, making accurate species- and strain-level identification essential. Potential carriage of AMR determinants in certain strains further emphasizes the need for comprehensive genomic and phenotypic safety assessment before their use in animal production (Berić *et al.*, 2018). In this context, the broader concerns associated with antimicrobial use in agriculture and the emergence and dissemination of AMR reinforce the importance of developing safe alternatives and carefully evaluating probiotic interventions (Manyi-Loh *et al.*, 2018). Although *Bacillus* probiotics have demonstrated antimicrobial, immunomodulatory, and gastrointestinal benefits in several animal species, including poultry, pigs, and ruminants, these effects should not be generalized across all strains or production conditions (Mingmongkolchai and Panbangred, 2018). Reported improvements in poultry growth and gut health, intestinal morphology and diarrhea control in pigs, and fiber digestion and milk production in ruminants (Sun *et al.*, 2013; Mun *et al.*, 2021) illustrate their potential but also emphasize the importance of host- and strain-specific validation.

Regulatory requirements and the absence of universally standardized protocols for assessing probiotic identity, safety, efficacy, dosage, and stability remain additional barriers to wider adoption (Elshaghabe *et al.*, 2017). Probiotic strains intended for commercial use must satisfy appropriate safety and efficacy criteria, and comprehensive evaluation can be both time-consuming and costly. Furthermore, differences in regulatory frameworks among countries can complicate the development, registration, and international commercialization of *Bacillus*-based products. Standardized approaches for evaluating probiotic performance under realistic farm conditions would therefore improve comparability among studies and strengthen the evidence base for commercial application.

Economic and practical considerations may also restrict adoption, particularly in resource-limited production systems. The cost of probiotic products, formulation, storage, and regular supplementation must be justified by measurable improvements in productivity or animal health. Because probiotic effects may not always be immediately visible to farmers, uncertainty regarding economic returns can further discourage adoption, particularly among small-scale producers (Elshaghabe *et al.*, 2017). Nevertheless, the potential of *Bacillus*-based probiotics to reduce dependence on conventional antimicrobials and minimize antimicrobial residues provides an important rationale for their continued development within sustainable livestock production strategies (Razafindralambo *et al.*, 2025).

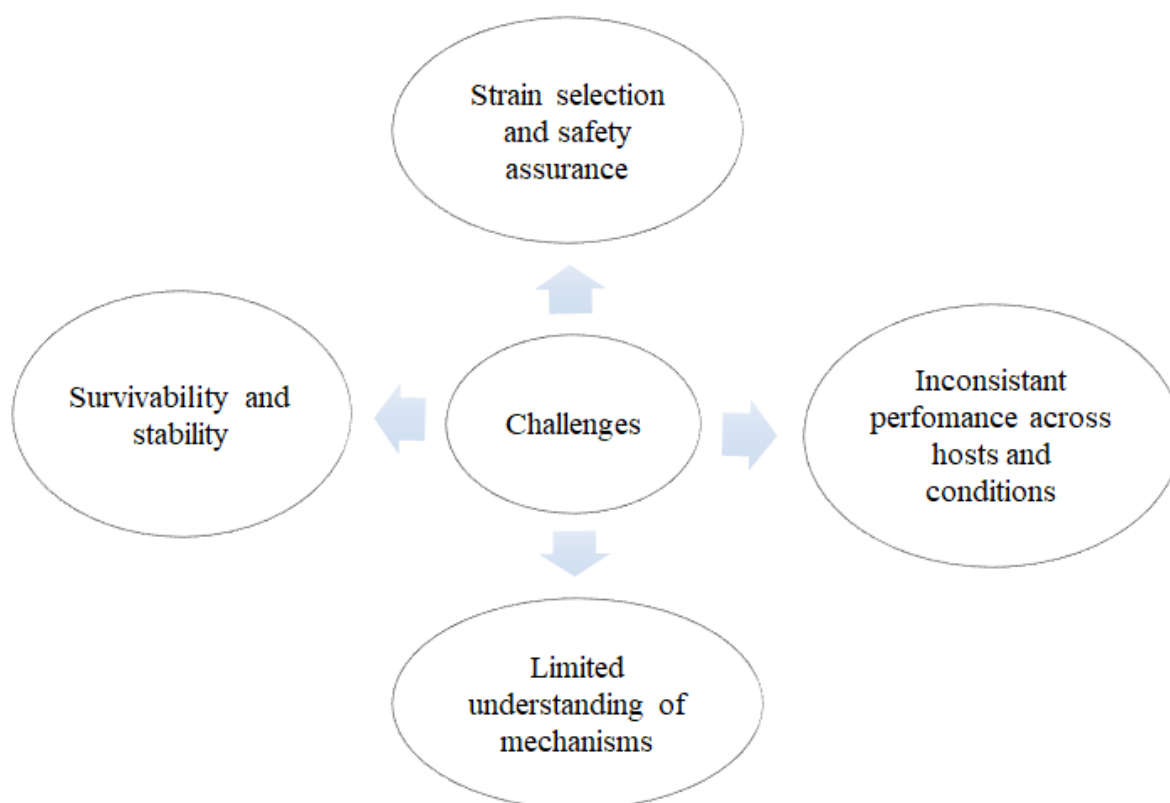


Figure 3. Challenges and limitations associated with the production and application of *Bacillus*-based probiotics.

Recent evidence supporting the use of *Bacillus* as an alternative to conventional antimicrobial interventions has therefore generated substantial interest (Nicolas, 2025). Their resistance to gastrointestinal and processing stresses, capacity to influence intestinal microbial communities and nutrient utilization, production of antimicrobial compounds, and competition with pathogens for nutrients and adhesion sites provide a strong biological basis for their application (Baruzzi *et al.*, 2011; Coertze, 2015; Zhang *et al.*, 2017; Khaneghah *et al.*, 2020). However, these properties should be considered within a broader framework of strain-specific safety, efficacy, regulatory compliance, economic feasibility, and farm-level implementation. Thus, *Bacillus* probiotics should be regarded not simply as universal replacements for antibiotics but as strain-specific biological tools whose effectiveness depends on appropriate selection, formulation, dosage, host compatibility, and production conditions. Figure 3 illustrate the challenges and limitations associated with the production and application of *Bacillus*-based probiotics.

7. Recent advances and trends

The use of *Bacillus* spp. as probiotics in animal production has expanded substantially in recent years, driven by their endospore-forming capacity, environmental resilience, and diverse beneficial effects on animal health and productivity (Elshaghabee *et al.*, 2017). Their ability to withstand the high temperatures and other stresses associated with feed processing, storage, and gastrointestinal transit has made spore-forming *Bacillus* species particularly attractive for incorporation into animal feed (Cutting, 2011). An important trend has been the increasing interest in spore-forming species such as *B. subtilis*, *B. licheniformis*, and *B. amyloliquefaciens* as alternatives or complements to conventional non-spore-forming probiotic microorganisms (Fritze and Claus, 1995).

Recent research has increasingly focused on the multifunctional properties of *Bacillus* probiotics, particularly their antimicrobial, immunomodulatory, and microbiota-modulating activities. Several strains exhibit inhibitory activity against important enteric pathogens, including *Salmonella*, *Escherichia coli*, and *Clostridium perfringens*, thereby providing a potential means of reducing pathogen-associated disease and antimicrobial use (Elshaghabee *et al.*, 2017). This development is consistent with broader efforts to reduce AMR through the restriction of antibiotic growth promoters and the adoption of alternative strategies for maintaining animal health and productivity (Miller *et al.*, 2022). At the same time, increasing attention has been directed toward the capacity of *Bacillus* probiotics to modulate intestinal microbial communities and enhance host immune responses (Yu *et al.*, 2022). For example, supplementation with *B. subtilis* has been associated with improved intestinal morphology in broiler chickens, including increased villus height and crypt depth, which may contribute to enhanced nutrient absorption and growth performance (Abudabos *et al.*, 2019). Similarly, *Bacillus*-based probiotics have been associated with improved feed conversion and reduced diarrhea, particularly in weaned piglets (Wang *et al.*, 2021b).

Another emerging trend is the development of multi-strain probiotic and synbiotic formulations. These products combine complementary *Bacillus* strains with prebiotics or other beneficial microorganisms with the aim of producing additive or synergistic effects (Giacchi *et al.*, 2016). Increasingly, such formulations are being designed according to animal species, production stage, and specific health or nutritional requirements, reflecting a shift toward more targeted probiotic interventions.

Advances in genomics and metagenomics are further transforming the selection and characterization of probiotic *Bacillus* strains. These approaches facilitate the identification of genetic and functional traits associated with probiotic performance, including adhesion, enzymatic activity, antimicrobial compound production, stress tolerance, and interactions with the host microbiome (Grant *et al.*, 2018; Carroll *et al.*, 2020). Consequently, microbiome-informed and precision-based selection of strains may enable the development of probiotics tailored to specific animal species and production conditions.

The current advances indicate that *Bacillus* probiotics are evolving from broadly applied feed additives toward more targeted, multifunctional, and evidence-based interventions. Their potential to support animal health and productivity while contributing to reduced antimicrobial dependence positions them as promising components of sustainable animal production systems (Islam *et al.*, 2022). Future research should continue to clarify strain-specific effects, optimize formulation and delivery strategies, and improve understanding of *Bacillus*–host–microbiome interactions to achieve more consistent outcomes under commercial production conditions.

8. Future perspectives

The demonstrated health-promoting effects, spore-forming capacity, and environmental resilience of *Bacillus* species provide a strong foundation for their continued development as next-generation probiotics in animal production (Elshaghabee *et al.*, 2017). Future applications are likely to move beyond the conventional use of

probiotics as general feed additives toward more precise, strain-specific, and technology-enabled interventions designed for particular animal species, production stages, and health challenges (Hume *et al.*, 2011).

A major future direction is the identification and development of strains with defined functional characteristics. Advances in genomics, bioinformatics, and molecular biotechnology are facilitating the selection of *Bacillus* strains with desirable traits, including enhanced antimicrobial peptide production, extracellular enzyme activity, stress tolerance, and immunomodulatory capacity (Mazhar *et al.*, 2020). Species such as *B. subtilis* and *B. licheniformis* are known to produce a wide range of industrially and biologically important enzymes, including amylases and proteases, as well as antimicrobial compounds (Cutting, 2011). Targeted strain selection and functional characterization could therefore facilitate the development of probiotics optimized for specific livestock species and production conditions.

Integration with precision livestock farming (PLF) represents another promising direction. Real-time monitoring technologies can provide information on animal growth, feed intake, health status, and other physiological indicators, creating opportunities for more targeted probiotic supplementation (Ismail *et al.*, 2023). Linking these data with strain-specific probiotic interventions could improve the timing and dosage of supplementation, potentially increasing efficacy while minimizing unnecessary inputs and reducing dependence on antimicrobial treatments (Grant *et al.*, 2018).

The development of synergistic probiotic formulations is also expected to expand. Combining *Bacillus* strains with prebiotics or other beneficial microorganisms may enhance microbial establishment, stimulate beneficial intestinal communities, and improve nutrient utilization (Mohanty *et al.*, 2018; Kwoji *et al.*, 2021). Similarly, advanced delivery technologies, including nano- and micro-encapsulation, may improve spore protection during feed processing and gastrointestinal transit and help maintain probiotic viability and functional activity at the target site (Ismail *et al.*, 2023).

Another emerging area is the potential role of *Bacillus* probiotics in regulating physiological stress responses and the gut–brain axis. Understanding these interactions could broaden their application beyond growth promotion and disease prevention toward improving resilience, welfare, and performance under challenging production conditions such as weaning, transportation, and environmental stress (Cheng *et al.*, 2019). At the same time, the development or use of genetically improved *Bacillus* strains with enhanced probiotic characteristics will require rigorous biosafety assessment, appropriate regulatory oversight, and consideration of public acceptance (Jeżewska-Frąckowiak *et al.*, 2018).

The *Bacillus* spp. have considerable potential as next-generation probiotics for modern animal husbandry (Yang *et al.*, 2021). Continued integration of genomics, microbiome research, precision livestock technologies, advanced formulation and delivery systems, and comprehensive animal health management could enable more predictable and targeted applications. Such developments may ultimately strengthen the contribution of *Bacillus*-based probiotics to productive, resilient, welfare-oriented, and environmentally sustainable animal production systems.

9. Conclusions

The use of *Bacillus* species as probiotics represents a promising strategy for sustainable and efficient animal production. Their diverse benefits, including improved gastrointestinal health, enhanced immune function, better feed efficiency, and disease resistance, highlight their potential as alternatives to conventional antimicrobial interventions and as tools for addressing AMR and environmental sustainability. Advances in strain selection, genetic characterization, formulation, and delivery technologies have further expanded the potential applications of *Bacillus* probiotics across different animal production systems. However, challenges related to strain specificity, safety, regulatory requirements, variable efficacy, and integration into existing production practices remain. Future research should therefore focus on elucidating strain-specific mechanisms, host–microbiome interactions, and large-scale field efficacy to ensure consistent and reliable outcomes. Overall, continued development of *Bacillus*-based probiotics could contribute substantially to healthier, more productive, and sustainable animal production systems while reducing dependence on conventional antimicrobial interventions.

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Generative AI tools were used to assist in the preparation of the figures. Grammarly was used to review and edit the language for grammar, clarity, and readability. The authors reviewed and approved the final content and take full responsibility for the accuracy and integrity of the manuscript.

Authors' contribution

Md. Roisul Momen: Conceptualization of the review, design of the thematic framework, writing- original draft; Md. Tanvirul Islam and Al Arafat: Development of the literature search strategy, data curation, literature collection and sorting, formal analysis and synthesis of the collected data, validation of included studies, visualization (figure/table preparation); A. K. M. Ziaul Haque, Yosef Deneke and S. M. Lutful Kabir: formal analysis and synthesis of the collected data, writing - review & editing. All authors have read and approved the final manuscript.

Conflict of interest

None to declare.

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