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Sustainable Biocontrol Methods for the Suppression of Animal Parasites in Modern Livestock Production

Nitin Yadav[1], Asad Khan[2*], Dhawal Kumawat[3] and Ashwani Kumar Sharma[4]

[1]*Department of Veterinary Parasitology, Apollo College of Veterinary Medicine, Jaipur – 302031, Rajasthan, India*
[2]*Division of Animal Genetics and Breeding, ICAR – National Dairy Research Institute, Karnal – 132001, Haryana, India*
[3]*Department of Veterinary Medicine, College of Veterinary Science and Animal Husbandry, Nanaji Deshmukh Veterinary Science University, Jabalpur – 482001, Madhya Pradesh, India*
[4]*Department of Animal Nutrition, College of Veterinary Science and Animal Husbandry, Nanaji Deshmukh Veterinary Science University, Mhow – 453441, Madhya Pradesh, India*

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ABSTRACT

Parasitic infections remain among the most important constraints to livestock health productivity and long-term sustainability worldwide. In natural ecosystems the population size of organisms is regulated through a complex interaction of abiotic and biotic factors including climate, temperature, humidity, competition, predation and disease. Many parasites are naturally suppressed by predators, parasitoids and pathogenic microorganisms such as bacteria, fungi, protozoa and nematodes. However environmental conditions that regulate parasite populations vary across geographical regions and change over time often allowing parasites to proliferate under favorable conditions. In livestock systems, these natural regulatory processes are frequently disrupted by management practices, intensification of production and climate variability resulting in increased parasite burden and economic losses. Historically, parasite control has relied predominantly on synthetic chemical agents. Although effective, initially their extensive and often indiscriminate use has led to widespread antiparasitic resistance, environmental contamination, loss of biodiversity and concerns related to food safety and human health. These challenges have intensified the search for sustainable alternatives. Biological control has emerged as a promising approach that exploits natural enemies to suppress parasite populations while restoring ecological balance. This review synthesizes biological control strategies for livestock parasites, focusing on arthropods, helminths, and intermediate hosts. It examines the roles of predators, parasitoids, and pathogenic microorganisms, highlighting their mechanisms, applications, and limitations under field conditions. The review also explores future prospects, including biotechnology, nanotechnology, host genetic resistance, and climate-resilient livestock systems, providing a framework for integrating biological control into sustainable parasite management programs.

Introduction

Population dynamics of all living organisms are governed by a complex interplay of natural regulatory forces that operate continuously within ecosystems. These forces function as ecological checks and balances, ensuring that populations remain within limits compatible with resource availability and environmental stability. In undisturbed ecosystems, organisms live, reproduce, and die largely without direct human intervention, a process often described as natural control. Both abiotic factors such as temperature, humidity, rainfall, soil characteristics, and geography, and biotic factors including competition, predation, parasitism, and disease play fundamental roles in shaping population size and distribution. Weather conditions in particular exert a strong influence on the survival, development, and transmission of parasites and their hosts, resulting in marked spatial and temporal variation in parasite abundance (Alston, 2011). Among the organisms regulated by these natural pro-

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[*] **Corresponding author E-mail addresses:** asadjouravi@gmail.com (Asad Khan)
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cesses are parasites, broadly defined as organisms that derive nourishment and shelter from a host while causing physiological or pathological harm. Parasites include a wide range of taxa, encompassing endoparasites such as gastrointestinal nematodes and trematodes, as well as ectoparasites such as ticks, mites, flies, and lice. In natural systems, parasite populations are often suppressed by predators, parasitoids, and pathogenic microorganisms including bacteria, viruses, fungi, protozoa, and nematodes. However, environmental heterogeneity means that the same combination of regulatory factors may substantially reduce parasite populations in one geographical region while allowing them to proliferate in another. Moreover, parasites may evolve strategies to evade or overcome their natural enemies, occasionally reaching high population densities with severe consequences for host populations.(fig 1.)

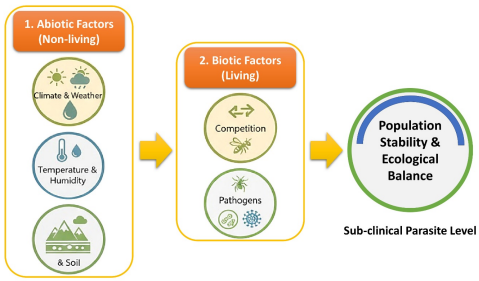


Fig. 1: Ecological regulatory forces and natural control of parasite populations

Livestock production systems are tightly interwoven with these ecological processes, yet modern animal agriculture has profoundly altered the conditions under which host parasite interactions occur. Intensification of livestock production, changes in grazing management, increased stocking densities, habitat modification, climate change, and global movement of animals have disrupted many of the natural regulatory mechanisms that previously kept parasite populations in check. As a result, parasitic infections have become one of the most persistent constraints to livestock health, productivity, and welfare worldwide (Singh et al., 2021). Parasites adversely affect growth rates, milk yield, reproductive efficiency, draught power, and overall animal performance, while also increasing susceptibility to secondary infections and contributing to morbidity and mortality, particularly in young and immunocompromised animals. The economic burden associated with parasitic diseases in livestock is immense, running into billions of dollars annually, with the greatest impacts observed in tropical and subtropical regions where climatic conditions favor parasite survival and transmission (Perry et al., 2002).

Historically, control of livestock parasites has relied heavily on synthetic chemical interventions, including anthelmintics, acaricides, and insecticides. These compounds have provided rapid and effective short-term suppression of parasite populations and have played a central role in improving animal productivity over the past several decades. However, the limitations of chemical-based parasite control are now widely recognized. Resistance to anthelmintics in gastrointestinal nematodes of sheep, goats, and cattle is widespread and continues to escalate, threatening the long-term viability of current control programs (Kaplan, 2004; Kaplan and Vidyashankar, 2012). Similarly, resistance in ticks, flies, mites, and other arthropod parasites to commonly used acaricides and insecticides has been documented across multiple continents (George et al., 2004). In addition to resistance, concerns regarding chemical residues in animal products pose risks to food safety, public health, and international trade.

Environmental consequences of chemical parasite control further underscore the need for alternative strategies. Antiparasitic drug residues can contaminate soil and water and negatively affect non-target organisms (Figure 2). Dung dwelling fauna such as beetles and flies plays critical roles in nutrient cycling, pasture aeration, and suppression of pest populations, yet are highly sensitive to residues of commonly used parasiticides (Wall & Strong, 1987). Disruption of these beneficial communities can exacerbate parasite problems and degrade ecosystem services essential for sustainable livestock production. These ecological and economic challenges have intensified interest in control approaches that align more closely with natural regulatory processes. Biological control, or biocontrol, represents such an approach. Biological control refers to the deliberate use or enhancement of natural enemies to reduce the adverse effects of a target organism and suppress its population to ecologically and economically acceptable levels (Alston, 2011). Unlike natural control, biological control involves human intervention to manipulate population dynamics through conservation, augmentation, or introduction of biological control agents. These agents, commonly termed biological control agents or BCAs, include predators, parasitoids, and pathogenic microorganisms that attack parasites directly or indirectly. Importantly, biological control aims not at eradication but at long term suppression of parasite populations through restoration of ecological balance (Table 1).

Table 1: Comparative analysis of chemical and biological control in animal parasitology

Feature	Chemical Control (Parasiticides)	Biological Control (BCAs)	References
Primary Mechanism	Direct toxicity to the parasite	Ecological interactions (Predation/ Parasitism)	Alston, 2011
Speed of Action	Rapid (Immediate suppression)	Gradual (Slow population decline)	Alston, 2011
Resistance Risk	Very High (Widespread globally)	Very Low (Co-evolutionary stability)	Kaplan, 2004 Kaplan and Vidyashankar, 2012
Residue Concerns	Present in milk, meat, and eggs	Minimal to none (Bio-degradable)	Alston, 2011
Non-Target Impact	High (Harmful to dung beetles/birds)	Selective (Specific to target species)	Wall and Strong, 1987 Alston, 2011
Cost Structure	High recurring costs per treatment	High setup cost; low long-term cost	Alston, 2011
Goal	Eradication of the population	Ecological balance and suppression	Alston, 2011 Perry et al., 2002

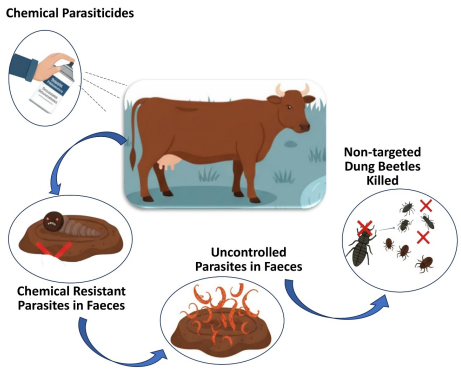


Fig. 2: Disruptive impact of chemical parasiticide residues on ecosystems, specifically showing the decline of beneficial dung beetles (parasitoids) and the resulting failure of natural parasite suppression

Over the past several decades, biological control has been widely and successfully applied in crop protection and vector management, and similar principles are increasingly being explored for animal parasites. Research has demonstrated the potential of diverse BCAs, including dung beetles, predatory mites, parasitoid wasps, entomopathogenic fungi, nematophagous fungi, bacteria, and entomopathogenic nematodes, to suppress key parasites of livestock. Advances in ecological understanding, molecular biology, and formulation technologies have further expanded the feasibility of biological control under field conditions (Eilenberg et al., 2001; Samish et al., 2004; Larsen, 2006). Recent years have also seen renewed interest in biological control as part of integrated parasite management frameworks that combine ecological principles with modern technologies. Climate change is altering parasite epidemiology by extending transmission seasons and expanding the geographical range of many parasites, thereby increasing uncertainty and risk for livestock producers. In this context, biologically based control strategies that are resilient, adaptable, and environmentally compatible are gaining prominence (Gaughan and Cawdell-Smith, 2015; Rose et al., 2016). Furthermore, integration of biological control with host genetic resistance, precision livestock farming, biotechnology, and novel delivery systems such as microencapsulation and nanotechnology offers new opportunities to enhance efficacy and consistency of BCAs under diverse production systems (Rai and Ingle, 2012; Alonso-Diaz and Fernandez-Salas, 2021). This article provides a comprehensive review of biological control of animal parasites in livestock systems, synthesizing ecological foundations, types of biological control agents, mechanisms of action, and practical application strategies. In addition, it adopts a forward-looking perspective by examining emerging technologies, climate resilient approaches, and research gaps that must be addressed to enable wider adoption. By bridging ecological theory with applied livestock health management, this review aims to provide a conceptual framework for incorporating biological control as a central component of sustainable and integrated parasite management programs.

Conceptual framework of biological control

Biological control refers to the use of living organisms or their products to reduce the population density or impact of a target pest or parasite. The organism used is termed a biological control agent. Biological control differs fundamentally from chemical control in that it relies on ecological interactions rather than direct toxic effects. Three principal strategies of biological control are recognized (Eilenberg et al., 2001) – (1). Conservation biological control aims to protect and enhance existing natural

enemies through habitat management reduced chemical use and modification of farming practices; (2). Augmentative biological control involves the periodic release of mass reared natural enemies to boost their population temporarily; (3) Classical biological control involves the introduction of a natural enemy from the native range of an invasive parasite following extensive risk assessment and quarantine. In livestock systems biological control must account for complex parasite life cycles host movement grazing patterns and climatic variability. Successful biological control requires host specificity synchronization with parasite life stages environmental compatibility and minimal risk to non-target species.

Importance and rationale of biological control in livestock parasite management

Chemical control using antiparasitic drugs has long been the dominant strategy for managing parasites in livestock production systems. Anthelmintics, acaricides, and insecticides have provided rapid and cost-effective suppression of parasites and have supported intensification of animal agriculture. However, the continued and often indiscriminate use of these chemicals has led to a progressive decline in their effectiveness. Resistance to antiparasitic drugs has now emerged as one of the most serious constraints to sustainable parasite control. In gastrointestinal nematodes of livestock, resistance to benzimidazoles, macrocyclic lactones, and imidazothiazoles is widespread, and multidrug resistance has become particularly problematic in small ruminant systems (Kaplan and Vidyashankar, 2012). Similarly, ticks have evolved resistance to multiple classes of acaricides including organophosphates, synthetic pyrethroids, and amidines, while comparable trends are evident in flies, lice, and other ectoparasites (George et al., 2004). Beyond resistance, chemical parasite control raises substantial environmental and public health concerns. Many antiparasitic compounds persist in soil and water, leading to bioaccumulation and adverse effects on non-target organisms such as beneficial insects, birds, fish, wildlife, and even domestic animals. Dung-associated fauna, which play a critical role in nutrient recycling and pasture health, are particularly sensitive to residues of commonly used parasiticides. In addition, chemical residues in milk, meat, and eggs pose risks to consumers and complicate compliance with increasingly stringent food safety regulations. Growing consumer demand for residue-free animal products has therefore intensified interest in alternative and environmentally responsible parasite control strategies (Waller, 2006). In this context, biological control has gained renewed attention as a viable and sustainable alternative or complement to chemical methods. Biological control involves the intentional use or enhancement of natural enemies to suppress parasite populations, thereby reducing their impact rather than attempting complete eradication. Under appropriate ecological conditions, biological control offers long-term sustainability that is often lacking in chemical-based approaches. A wide range of biological control agents can be exploited for parasite management, including predators (such as arthropods, mites, flies, beetles, amphibians, fish, birds, and rodents), parasitoids, and pathogenic microorganisms including fungi, bacteria, and protozoa (Kumar et al., 2021). Importantly, biological control aligns closely with the principles of integrated parasite management. Rather than functioning as a standalone solution, it complements other control measures such as grazing management, targeted selective treatment, nutritional interventions, and the exploitation of host genetic resistance. By reducing reliance on chemicals and lowering selection pressure for resistance, biological control enhances the resilience and sustainability of livestock production systems. Consequently, biological control is increasingly recognized not only as an alternative to chemical parasiticides but as a critical component of future livestock parasite management strategies.

Types of biological control agents in livestock parasite management

Biological control of parasites encompasses a broad spectrum of natural enemies that act through predation, parasitism, or pathogenicity to suppress parasite populations. These biological control agents (BCAs) include predators, parasitoids, bacteria, fungi, protozoa, and nematodes, each operating through distinct ecological and biological mechanisms (Table 2 and Figure 3). Unlike chemical control, which often aims at rapid eradication, biological control seeks to regulate parasite populations at ecologically tolerable levels while maintaining environmental balance. This approach aligns closely with sustainable livestock production and integrated parasite management strategies.

Figure 1: Classification and Mechanisms of Biological Control Agents (BCAs)

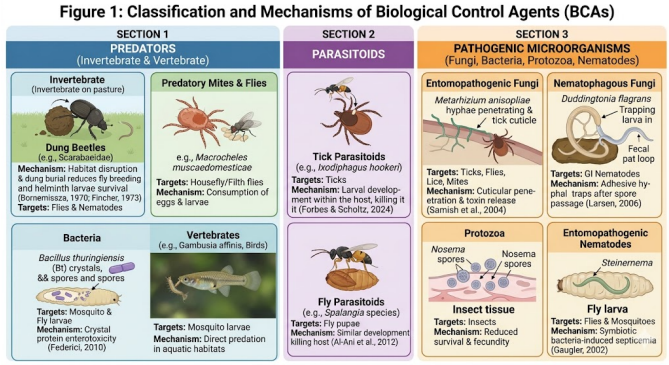


Table 2: Categorization of major biological control agents and their mechanism of action

Agent Category	Representative Species	Target Parasite(s)	Primary Mechanism	References
Predatory Insects	*Scarabaeidae (Dung Beetles)*	Flies and Nematodes	Habitat disruption and larval mortality	Waller, 2006 Wall and Strong, 1987
Predatory Mites	*Macrocheles muscae domesticae*	Housefly and Filth flies	Consumption of fly eggs and larvae	Alston, 2011
Parasitoids	*Ixodiphagus hookeri*	Ticks	Larval development within the host	Alston, 2011
Entomopathogenic Fungi	*Metarhizium anisopliae*	Ticks, Flies, and Lice	Cuticular penetration and toxin release	George et al., 2004
Nematophagous Fungi	*Duddingtonia flagrans*	GI Nematodes	Adhesive hyphal traps in fecal pats	Waller, 2006
Bacteria	*Bacillus thuringiensis (Bt)*	Mosquito and Fly larvae	Crystal protein (Cry) enterotoxicity	Alston, 2011
Nematodes	*Steinernema & Heterorhabditis*	Flies and Mosquitoes	Symbiotic bacteria-induced septicemia	Alston, 2011
Vertebrates	*Gambusia affinis (Mosquitofish)*	Mosquito larvae	Direct predation in aquatic habitats	Alston, 2011

Fig. 3: Classification and of various biological control agents (BCAs)

Predators as biological control agents

Predators represent one of the most diverse groups of BCAs and include both invertebrate and vertebrate species. Among invertebrates, arthropods play a particularly important role. Spiders prey on a wide range of insects and contribute to natural suppression of pest populations. Aquatic predators such as river prawns have been shown to prey on freshwater snails that act as intermediate hosts for trematode parasites (Sokolow et al., 2014). Predatory thrips, notably *Scolothrips sexmaculatus*, feed voraciously on spider mites and other small arthropods, with both larval and adult stages contributing to control (Mahr and Ridgway, 1993). Predatory mites such as *Macrocheles muscaedomesticae* are well adapted to manure-rich environments and consume eggs and larvae of houseflies and other filth flies, significantly reducing fly emergence in livestock facilities (Safaa et al., 2014; Axtell, 1986). Predatory flies, particularly *Hydrotaea aenescens*, have been successfully commercialized for indoor control of *Musca domestica* in Europe (Pirali, 2012). In addition, certain small flies such as *Mutilla glossinae* act as parasites of tsetse flies and show promise as BCAs in vector management programs (Oluwafemi, 2008). Dung beetles are among the most ecologically significant predators in grazing systems. By feeding on and rapidly burying dung, beetles of the family Scarabaeidae disrupt fly breeding sites and reduce survival of parasite eggs and larvae. Classical studies in Australia demonstrated that introduced dung beetle species markedly reduced bush fly and horn fly populations while simultaneously improving pasture quality (Bornemissza, 1970). Dung burial alters moisture and temperature within fecal pats, indirectly reducing the survival of gastrointestinal nematode larvae (Fincher, 1973). Subsequent work confirmed that dung beetles contribute to helminth control by reducing pasture contamination. Recent studies further emphasize their role in enhancing soil health and mitigating greenhouse gas emissions, strengthening their relevance under climate-resilient livestock systems (Slade and Roslin, 2016; Beynon et al., 2015). Vertebrate predators also contribute to parasite regulation. Fish such as *Gambusia affinis* and guppies effectively consume mosquito larvae and reduce vector populations (Walker, 2002), while black carp (*Mylopharyngodon piceus*) prey on snail intermediate hosts of zoonotic trematodes (Hung et al., 2013). Birds, including oxpeckers and domestic poultry, remove ticks and insect larvae from hosts and grazing environments. Amphibians, reptiles, and earthworms further contribute to natural parasite suppression, with earthworms consuming nematode larvae during soil and fecal ingestion, thereby facilitating natural biological control of trichostrongylid nematodes.

Parasitoids in livestock parasite control

Parasitoids are insects whose immature stages develop within or on a host, ultimately killing it. They are often highly host-specific, minimizing risks to non-target organisms. Parasitoid wasps and flies are particularly important in controlling arthropod parasites. *Ixodiphagus hookeri*, a parasitoid of ticks, has been reported across multiple continents (Gahan, 1934; Trjapitzin, 1985; Hu

et al., 1993). Although laboratory studies demonstrate its potential, large-scale field application has been constrained by challenges in mass rearing and synchronization with tick life cycles (Forbes and Scholtz, 2024). In contrast, parasitoids of fly pupae such as *Spalangia* and *Muscidifurax* species have been successfully integrated into dairy and poultry fly management programs (Al-Ani et al., 2012), illustrating the practical utility of parasitoids in livestock systems.

Pathogenic microorganisms as biological control agents

Pathogens constitute one of the most intensively studied categories of BCAs. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* infect arthropods through direct cuticular penetration and kill hosts via tissue invasion and toxin production. These fungi have demonstrated efficacy against ticks, flies, mosquitoes, lice, and mites under laboratory and field conditions (Samish et al., 2004). Their ability to persist in soil enhances long-term suppression, although environmental factors such as humidity and temperature strongly influence effectiveness. Advances in formulation and delivery technologies have substantially improved their field performance in recent years (Alonso-Díaz and Fernández-Salas, 2021). Nematophagous fungi represent a major breakthrough in helminth control. Species such as *Duddingtonia flagrans* trap and destroy nematode larvae using specialized hyphal structures. When administered orally, spores survive passage through the gastrointestinal tract and germinate in feces, reducing larval development on pasture (Larsen, 2006). Field trials have consistently demonstrated reductions in pasture contamination and improvements in animal performance. Continued research has focused on optimizing dosing strategies and integrating fungal biocontrol with grazing management under diverse climatic conditions (Vilela et al., 2012; Rose et al., 2016). Bacterial agents also play a critical role. *Bacillus thuringiensis* produces crystalline toxins that disrupt the gut epithelium of insect larvae and has been widely used in mosquito and fly control programs (Federici, 2010). Different subspecies target specific insect groups, enhancing selectivity and safety. *Streptomyces* species produce a range of antiparasitic metabolites, including avermectins, which revolutionized parasite control and continue to inspire research into novel bioactive compounds. Protozoan pathogens such as *Nosema* species infect insects and reduce survival and fecundity, while microsporidia can damage intramolluscan stages of trematodes (Soulsby, 1968). Entomopathogenic nematodes of the genera *Steinernema* and *Heterorhabditis* infect insects and release symbiotic bacteria that rapidly kill the host, making them effective and environmentally safe BCAs (Gaugler, 2002). These nematodes have been applied against fly larvae and mosquitoes and are regarded as safe for humans, livestock, and plants.

Application of biological control in the field and its integration with livestock management

Biological control in field conditions is generally implemented through two complementary approaches: conservation of existing natural enemies and the introduction of new natural enemies aimed at establishing self-sustaining populations, commonly referred to as classical biological control. Conservation-based strategies focus primarily on minimizing disruptions to naturally occurring antagonists of parasites, particularly through reduced and strategic use of parasiticides, as excessive chemical intervention is widely recognized as a major constraint to the effectiveness of biological control agents. This principle forms the foundation of integrated parasite management (IPM), which seeks to balance chemical and biological control by limiting treatments to economically justified levels and applying them in ways that reduce non-target impacts (Leathwick and Besier, 2014). The influence of anti-parasitic compounds on beneficial organisms depends not only on their inherent toxicity but also on application timing, persistence, and spatial placement, with evidence showing that targeted treatments, use of less persistent compounds, and avoidance of sensitive life stages of natural enemies can substantially reduce collateral damage (Sands and Wall, 2016; Vercruysse et al., 2018). Techniques such as spot treatments, strip applications, pasture rotation, and maintenance of refugia enable natural enemy populations to persist alongside treated areas, thereby enhancing long-term biological regulation of parasites. In contrast, classical biological control involves the deliberate introduction of carefully selected natural enemies following extensive research on parasite biology, host specificity, ecological safety, and quarantine screening to prevent unintended consequences. Successful establishment depends on precise synchronization with parasite life cycles, appropriate release environments, and continued management practices that minimize disturbance to the introduced agents. Although this approach is resource-intensive and requires long-term commitment and regulatory oversight, it can deliver durable and cost-effective outcomes when successful (Hajek et al., 2016; van Lenteren et al., 2018). Effective field implementation further relies on integration with broader livestock management systems, including pasture management, controlled augmentative releases in confined systems, and strong farmer education and extension support. Economic assessments increasingly demonstrate that while

initial investments in biological control and IPM may be higher, the long-term benefits, such as reduced chemical dependence, delayed resistance development, and improved environmental sustainability often outweigh the costs (Kaplan and Vidyashankar, 2012; Charlier et al., 2014; Rose et al., 2016).

Future Perspectives in Biological Control

The future of biological control holds substantial promise for sustainable parasite management in livestock and agricultural systems, though current use remains limited. Advances in biotechnology provide opportunities to genetically improve microbial and invertebrate agents for enhanced virulence, host specificity, and environmental tolerance. Genes responsible for antagonistic effects in fungi, bacteria, nematodes, and insects can be manipulated to produce more effective biological control agents (BCAs). For example, recombinant strains of *Bacillus thuringiensis* var. *israelensis* (Bti) engineered with insecticidal genes from Bti, *B. sphaericus*, or other variants have demonstrated up to tenfold increased toxicity against target vectors while remaining safe for humans, livestock, and non-target organisms (Federici, 2010; Khater, 2012; Wang and St Leger, 2007b). Similarly, genetically modified fungi incorporating toxins such as scorpion or mite toxins can accelerate host mortality and enhance BCA effectiveness (Wang and St Leger, 2007a; Ulrichs et al., 2006). Nanotechnology offers further innovation by improving the stability, persistence, and targeted delivery of BCAs. Surface-charged hydrophobic nano-silica particles (3–5 nm) have shown efficacy against veterinary ectoparasites, representing a green alternative to chemical treatments (Rai and Ingle, 2012; Kah et al., 2018; Benelli, 2016). Microencapsulation of BCAs protects against environmental stresses such as ultraviolet radiation and desiccation, prolonging shelf-life and enhancing biological activity; this approach has been applied to fungi, bacteria, essential oils, and other bioactive substances (Azeredo, 2008; Silva et al., 2014). Collectively, these technological advances address major limitations of traditional biological control, such as slow killing rates, environmental instability, and reduced efficacy under field conditions, while offering prospects for integration into next-generation integrated parasite management programs. Recent studies emphasize that combining biotechnology, nanotechnology, and formulation innovations can produce highly efficient, environmentally safe, and economically viable BCAs for livestock parasites and vector-borne diseases (Chokriwal et al., 2015; de Oliveira et al., 2023; Baldiviezo et al., 2023; de Jesus Seabra et al., 2024).

Advantages and limitations of biological control

Biological control is a highly specific and environmentally safe approach to parasite management and is widely regarded as a sustainable alternative to chemical-based control methods. In most cases, predators, parasitoids, or pathogenic organisms introduced for biological control act selectively on target parasite species, thereby minimizing adverse effects on non-target organisms and reducing environmental contamination. Once established, biological control agents are often capable of maintaining their populations without repeated human intervention, allowing long term suppression of parasite populations. This self-sustaining nature makes biological control economically attractive over time, particularly when compared with the repeated costs associated with chemical treatments. In addition, reduced reliance on antiparasitic drugs lowers selection pressure for resistance, a major concern in livestock parasite management worldwide (Kaplan, 2004; Waller, 2006). Biological control also supports broader ecosystem services such as biodiversity conservation, nutrient cycling, and pasture health, which are often disrupted by chemical residues (Wall and Strong, 1987).

Despite these advantages, biological control has several limitations that restrict its widespread adoption. The effectiveness of biological control agents can vary considerably under field conditions due to environmental factors such as temperature, humidity, and management practices (Table 3). Biological control generally acts more slowly than chemical treatments and therefore does not provide immediate parasite suppression, which can be problematic during severe outbreaks. Complete elimination of parasites is rarely achieved because biological control agents depend on the presence of the host population for survival and typically reduce rather than eradicate parasites (Eilenberg et al., 2001). Furthermore, the development, mass production, storage, and release of biological control agents require substantial planning, technical expertise, and initial financial investment. For these reasons, biological control is most effective when used as a component of integrated parasite management systems that combine grazing management, selective treatment, and host resistance rather than as a stand-alone solution (George et al., 2004).

Table 3: Advantage and Disadvantages of Biological Control

Feature	Advantage	Disadvantage	References
Specificity	Targets only specific parasites, protecting biodiversity.	Can be fickle; agents might switch targets or disrupt food chains.	Alston, 2011 Federici, 2010
Sustainability	Once established, agents are self-perpetuating.	It is a slow process compared to chemical treatments.	Alston, 2011 Wang and St Leger, 2007a
Cost	Cost effective in the long run as it requires one time setup.	High initial costs for research, development, and introduction.	Alston, 2011 Chokriwal et al., 2015
Effectiveness	Naturally inclined to seek out and reduce parasite loads.	Cannot completely eradicate a parasite; only reduces population levels.	Alston, 2011 Perry et al., 2002

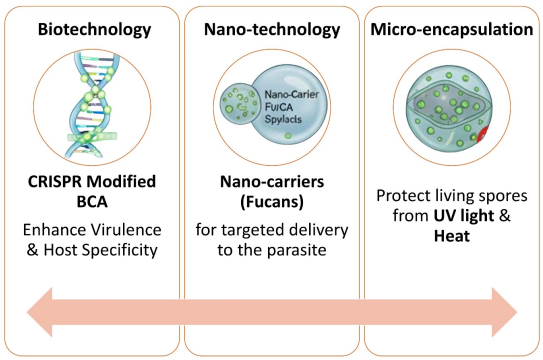


Fig. 4: Integration of biotechnological innovations, such as microencapsulation and nanotechnology, to enhance the stability and targeted delivery of biological control agents in veterinary medicine

Conclusion

The control of parasites in livestock has traditionally relied on chemical methods; however, their long-term effectiveness is increasingly constrained by the development of parasite resistance, risks to animal and human health, environmental contamination, and unintended effects on non-target organisms. In this context, biological control has emerged as a viable and sustainable alternative and is now recognized as a core component of integrated parasite management strategies. By harnessing natural enemies and ecological processes, biological control addresses many of the inherent limitations of chemical-based approaches while supporting ecosystem health and long-term productivity. Recent advances between 2015 and 2026 have highlighted the importance of integrating biological control with climate smart livestock management, precision delivery systems, host genetic resistance, and ecosystem-based regulation of parasites. Progress in formulation technologies, microbiome-based interventions, nanotechnology, and microencapsulation has enhanced the efficacy, stability, and field performance of biological control agents, while biotechnological innovations have enabled the identification and genetic improvement of both existing and novel agents. Despite these advances, several challenges remain, including concerns regarding impacts on native biodiversity, limitations in large scale production and distribution, and the continued reluctance of farmers to replace or reduce chemical treatments. Nevertheless, ongoing research and technological innovation provide strong optimism that biological control strategies will overcome these barriers and assume an expanded role as a cornerstone of sustainable parasite management and livestock production in a changing climate.

Conflict of Interest

Authors declare no competing interest.

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