Tropical Biomedicine 41(4): 533-542 (2024)
https://doi.org/10.47665/tb.41.4.015

REVIEW ARTICLE

Metarhizium anisopliae: current status and future in hard ticks control in Asia

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ARTICLE HISTORY

Received: 20 June 2024
Revised: 18 August 2024
Accepted: 19 August 2024
Published: 31 December 2024

ABSTRACT

Ticks exert a significant economic impact on the livestock industry, particularly in Asian regions. Presently, chemical acaricides constitute the primary method employed to combat tick infestations in livestock, but their use carries adverse environmental consequences. Overreliance on acaricides has contaminated milk and meat products with chemical residues while fostering tick resistance to these agents due to improper and intensive application. Various alternative methods have been explored, including using vaccines to manage tick populations. However, the efficacy of these treatments varies and is often limited when applied separately. Among these alternatives, entomopathogenic fungi like *Metarhizium anisopliae* appear to be a promising candidate for tick population control. This fungus can be used independently and in conjunction with other products. This review article explores the current and future prospects of *M. anisopliae*, where the existing gaps and future directives for using this fungus to control hard ticks in Asian countries are highlighted.

Keywords: Acaricide resistance; biocontrol; Ixodidae; livestock; entomopathogenic fungi.

INTRODUCTION

Asia is the largest continent globally, with tropical, subtropical, and temperate climates that host extensive species, contributing to a high degree of biodiversity. The agricultural sector plays a crucial role in the economic development of South and Southeast Asian countries, providing employment and reducing poverty within the community (Liu *et al*., 2020). The exponential economic growth and urbanization of Asian countries over the last two decades have significantly increased the demand for cattle and buffalo products, including beef and milk (OECD-FAO, 2018). Asia has emerged as a major global contributor to cattle and buffalo production, representing approximately 39% of the global stock (Roche *et al*., 2020). India leads the region in cattle and buffalo inventory, followed by China, Pakistan, Bangladesh, Myanmar, Indonesia, Nepal, Vietnam, Thailand, and the Philippines (FAO, 2022a). However, the persistent challenge of ticks and tick-borne diseases poses a constant threat to the economic stability of the livestock industry in Asian countries.

Ticks exert a tremendous financial impact on the livestock industry, particularly in Asian countries with subtropical and tropical regions (Iqbal *et al*., 2022). *Rhipicephalus* ticks, particularly *Rhipicephalus* (*Boophilus*) *microplus* and *R.* (*B.*) *annulatus*, are major vectors transmitting cattle diseases in the livestock industry, resulting in significant economic losses (Hosseini-Chegeni *et al*., 2019). Mortality, treatment costs, and acaricide applications contribute most to the economic losses associated with ticks and tick-borne diseases, while milk and weight loss contribute to the financial burden to a lesser extent (Kivaria, 2006). A study by Ashfaq *et al*. (2015) assessed the impact of tick infestation by evaluating the value of milk loss, the cost of veterinary treatment, and the value of weight loss in affected animals, revealing that tick infestation is a primary factor causing financial loss among dairy cattle farmers. In India, cumulative losses of USD 595.07 million were attributed to milk loss, treatment costs, and leather loss due to tick infestation, with an additional total loss of USD 191.15 million due to tick-borne diseases (Singh *et al*., 2022; Khan *et al*., 2022).

Ectoparasite control is traditionally achieved by using chemical acaricides such as pyrethroids and organophosphates (Cella *et al*., 2023). Asia has utilized large quantities of pesticides, averaging 0.65 million tons per year over the past three decades, with China and India recording the highest pesticide consumption (FAO, 2022b). There is a large-scale establishment of multi-acaricides resistant tick populations in tropical and subtropical regions been reported (Shanmuganath *et al*., 2021). Studies on alternative approaches encompass biological control, such as the use of botanical extracts (Ajith Kumar *et al*., 2016; Bravo-Ramos *et al*., 2021), entomopathogenic nematode (de Mendonna *et al*., 2019; Singh *et al*., 2018), tick symbiont bacteria (Khoo *et al*., 2016), and combination of entomopathogenic nematode with plant extract (Monteiro *et al*., 2021) can play pivotal roles in achieving a comprehensive and sustainable management approach besides mitigating the selective pressures exerted on tick populations through chemical control.

Biological control of ticks using entomopathogenic fungi (EPF) such as *Metarhizium anisopliae* (MA), *Beauveria bassiana*, *Aspergillus oryzae*, and *Lecanicillium lecanii* has been evaluated (Angelo *et al*., 2010; Meirelles *et al*., 2023; Msangi *et al*., 2022; Sullivan *et al*., 2022). Among the EPFs, MA and *B. bassiana* are the most studied species, with several commercially available formulations developed (Weeks *et al*., 2020). A study conducted by Mesquita *et al*. (2023) reported that MA can affect the gut bacterial diversity of engorged female ticks and demonstrated that the myco-acaricidal efficacy of MA would not be affected if the host is under antibiotic therapy, suggesting MA as a promising biological acaricidal agent. Therefore, this review paper intends to draw attention to MA for its current status, challenges and future advancement towards hard tick control in Asian countries by employing the online database Clarivate™ and SCOPUS as the primary search engine.

Metarhizium anisopliae: Current Status of Livestock Tick Control in Asia

Extensive research has been conducted globally to explore the pathogenicity of *Metarhizium* spp. as a biological control agent against ticks, with notable contributions from countries across various continents, such as Brazil and the USA, dating back to 1997 (Correia *et al*., 1998; Zhioua *et al*., 1997). In Asia, the inception of investigations into utilizing *Metarhizium* spp. for tick control was documented in 2001 in Israel (Gindin *et al*., 2001). Israel emerged as a prominent contributor to research in this field in Asia during the early 20th century.

A comprehensive collection of 298 records on the biological control of ticks using *Metarhizium* spp. from around the world, spanning the years 1997 to 2023, was available in the online database Clarivate™ and SCOPUS. Among the 298 records, 142 articles were documented in the past 10 years. The primary *Metarhizium* spp. being studied previously include *M. anisopliae*, as evidenced by numerous recent publications (de Almeida *et al*., 2022; Barbieri *et al*., 2023; da Paixто *et al*., 2023; Guimapi *et al*., 2023; Lee *et al*., 2023; Marzouk & Ali, 2023; Meirelles *et al*., 2023; Saciloto-de-Oliveira *et al*., 2023), as well as *M. brunneum* (Ment *et al*., 2010; Sullivan *et al*., 2020; Sullivan *et al*., 2021; Sullivan *et al*., 2022), *M. robertsii* (Goldsmith *et al*., 2021; Marciano *et al*., 2021; Fiorotti *et al*., 2022), and *M. pemphigi* (Lorenz *et al*., 2020).

Despite Asia being the largest continent and hosting a substantial livestock industry, the records from the past 10 years indicate a disproportionately low representation. Out of the 142 global records, there were only 16 entries reporting the utilization of *Metarhizium* spp. as a biological control against ticks in Asia (Figure 1). Of these 16 entries, a mere four articles specifically addressed the efficacy of *M. anisopliae* against livestock ticks (Table 1). Criteria for the paper to be included for review were published within 10 years from 2023, a research article, reporting the efficacy of *M. anisopliae* against livestock ticks. The screening and selection process is described in Figure 2.

Figure 1. Records of *Metarhizium* spp. against livestock ticks in Asia. (South Korea 5, Israel 3, China 3, Iran 2, Malaysia 2, Turkey 2, India 1).

Table 1. Current research of *Metarhizium anisopliae* as a biological control agent against livestock ticks in Asia

Country	Tick Species	Host	Experiment	Conc. Tested	Formulation	Result	Reference
China	*Haemaphysalis qinghaiensis* (nymph)	Sheep	Laboratory	$1x10^5 – 1x10^9$	Conidia suspensions mixed with 0.05% Tween 80	62% – 100% mortality	Ren *et al.*, 2016
	Haemaphysalis qinghaiensis (engorged female)			$1x10^6 – 1x10^8$		73% – 100% mortality	Ren *et al.*, 2014
Korea	*Haemaphysalis longicornis* (nymph)	Collected from grass	Laboratory	$1x10^6 – 1x10^8$	Conidia suspensions added with 0.03% siloxane	10% – 70%	Lee *et al.*, 2019
			Semi-field test	$1x10^8$		75% – 90% (30 days)	
Turkey	*Hyalomma anatolicum excavatum* (nymph & engorged female)	Cattle	Laboratory	$1x10^6 – 1x10^8$	0.03% aqueous Tween 80	55% – 100% mortality (nymph) Not susceptible toward MA (Engorged female)	Butt *et al.*, 2016

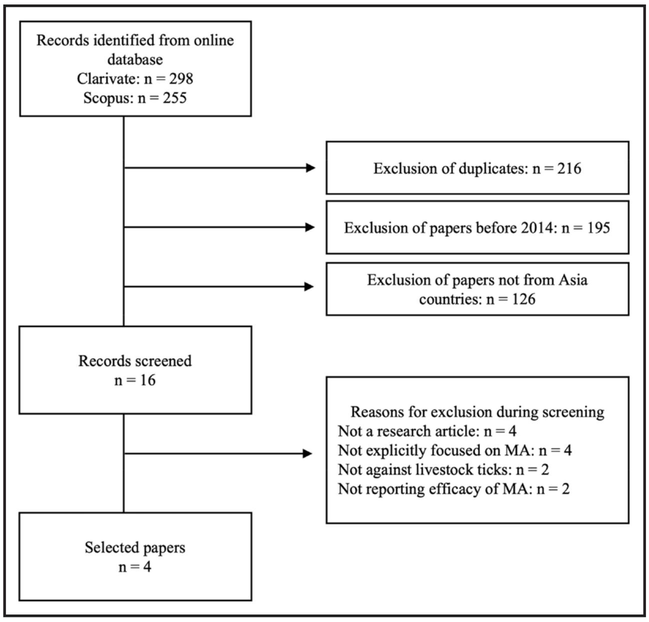

Figure 2. The screening and selection process of articles for current research of *Metarhizium anisopliae* as a biological control agent against livestock ticks in Asia.

The previous studies on the efficacy of MA against livestock ticks, as delineated in four specific articles (refer to Table 1), spans three distinct countries – Korea, Turkey, and China. China contributed to two studies conducted by the same researcher in 2014 and 2016, with a focus on assessing the efficacy of MA against engorged female and nymph stages of *Haemaphysalis qinghaiensis*. The Chinese studies (Ren *et al*., 2014; Ren *et al*., 2016) specifically evaluated the impact of MA on engorged female and nymph stages of *H. qinghaiensis*, demonstrating mortality rates ranging from 50% to 100%. In 2016, a Turkish publication reported on the efficacy of MA against *Hyalomma anatolicum excavatum* nymphs, showcasing mortality rates ranging from 73.3% to 100%. The most recent Korean study focused on *Haemaphysalis longicornis* in both laboratory and simulated field trial conditions, with mortality rates exceeding 50%. Notably, nymphs under semi-field conditions exhibited lower susceptibility to MA, achieving maximum mortality of 90% after 30 days.

It is noteworthy that, to date, there are no documented instances in the literature of field trials or large-scale implementation of MA against livestock ticks in Asia. Meanwhile, on a global scale, initiatives have been undertaken to initiate investigations into the efficacy of MA through field trials, as documented by Webster *et al*. (2017) and Barbieri *et al*. (2023). The findings from these studies reveal that the application of MA can eradicate more than 50% of the targeted tick populations. While extant literature indicates the potential of MA to induce tick mortality, particularly in controlled environments (Fernandes *et al*., 2012; Fernández-Salas *et al*., 2016; Alonso-Díaz & Fernández-Salas, 2021); its adoption as an alternative control method in Asia remains comparatively limited, lagging behind other countries as indicated in the literature search in Figure 2. The promising early findings highlight the need for additional research and exploration to fully realize the promise of MA for tick management in Asian regions. This underscores the significance of conducting further scientific research and developing novel techniques to maximize the benefits of MA. While current research indicates MA's potential, much more remains to be learned regarding its uses and efficacy. Thorough research is required to determine how MA can effectively meet the specific tick control challenges unique to Asia.

Chemical Control: An Overview of Acaricides Resistance in Asia

Acaricides, chemical agents specifically formulated for the management of ticks and mites, have constituted a pivotal component in pest control strategies. Despite the efficacy demonstrated by certain acaricides in rapidly mitigating tick populations, the protracted utilization of a singular acaricide has engendered a surge in tick resistance (Beys-da-Silva *et al*., 2020; Githaka *et al*., 2022; Barbieri *et al*., 2023). This phenomenon of acaricide resistance is not a recent development, as historical records indicate its recognition as early as 1937, with resistance surfacing after more than four decades of Arsenic employment (Newton, 1967). Acaricide resistance extends beyond the mere inability to eradicate ticks, encompassing a multifaceted challenge involving the proliferation of tick populations into non-endemic regions (Yawa *et al*., 2022).

Over the preceding half-decade, a limited number of countries, specifically four globally apart from Asia, have undertaken investigations into acaricide resistance in livestock, yielding significant insights from the United States, Brazil, South Africa, and Nigeria. Research originating from the United States has divulged disparate mortality rates (ranging from 0% to 59%) in engorged female *R. microplus* when exposed to pyrethroids, as documented by Klafke *et al*. (2019). In stark contrast, there is a heightened susceptibility (88% to 100% mortality) observed in response to a pyrethroid-organophosphate combination, and an increased mortality trend in *R. microplus* larvae upon exposure to ivermectin, as elucidated by Villar *et al*. (2019).

Comparable findings have been documented in Brazil, demonstrating elevated resistance levels in engorged female *R. microplus* to pyrethroids (cypermethrin), with mortality rates recorded at 26.2%. Additionally, substantial resistance in *R. microplus* larvae to pyrethroids has also been observed, as highlighted in the same research conducted by Higa *et al*. (2020). Recent South African research findings, as reported by Yawa *et al*. (2022), indicate the emergence of resistance in *R. decoloratus* larvae to amidines, organophosphates, and pyrethroids. A parallel study in Nigeria, conducted by Akande *et al*. (2020), underscores low resistance in engorged female *R. microplus* to formamidine, with emerging resistance patterns observed against pyrazoles, macrocyclic lactones, and pyrethroids.

Within the Asian context, a noticeable gap or missing information when it comes to discussing acaricide resistance in livestock in Asia. Recognizing the urgent need to fill this information gap, the subsequent table aims to furnish a comprehensive elucidation of the prevailing status of acaricide resistance within tick populations across the Asian region. This effort aims to assess the current status of acaricide resistance in livestock ticks across Asia. By providing comprehensive data on the resistance levels, we hope to gain clearer insights into the extent and severity of acaricide resistance. This knowledge is crucial for devising effective strategies to manage and mitigate acaricide resistance, thereby enhancing livestock health and productivity in Asia.

In this section, keywords: (chemical OR chemicals OR acaricide OR acaricides) AND (resistant OR resistance) AND (tick OR ticks) AND (livestock) were used for the literatures search. Initially, the search yielded 238 results, but this number was narrowed down to 173 after excluding papers published before 2013. Of these, 119 research papers were selected. Among these, only 13 Asian countries with papers that related to the subject, with 33 studies matching our keyword criteria. Comprehensive studies on acaricide resistance in ticks have been conducted primarily in two Asian countries – India and Pakistan (Table 2). The research focused on two predominant tick species: *R. microplus* and *H. anatolicum*. The findings revealed that *R. microplus* exhibited a higher resistance level, particularly demonstrating a level 4 resistance to Deltamethrin (Godara *et al*., 2019), whereas the majority of others ranged from susceptible to level 2. *Hyalomma anatolicum*, a significant etiologic agent of tropical theileriosis (Jongejan & Uilenberg, 2004), displayed resistance levels falling between susceptible and level 1. A notable trend emerged, indicating an increasing resistance of ticks in these two Asian countries to various chemical classes. The primary classes affected include pyrethroids (Deltamethrin and Cypermethrin) (Shyma *et al*., 2013; Singh *et al*., 2015; Godara *et al*., 2019; Solanki *et al*., 2020; Sagar *et al*., 2020; Sindhu *et al*., 2022), followed by pyrazoles (Fipronil) (Gupta *et al*., 2020; Kamran *et al*., 2020), organophosphorus (Coumaphos and Diazinon) (Shyma *et al*., 2013; Sagar *et al*., 2020), and, lastly, macrocyclic lactones (Ivermectin) (Sagar *et al*., 2020; Kamran *et al*., 2020).

Table 2. Current acaricides resistance status of ticks in Asia

Country	Tick	Test	Acaricide	Resistance Factor	Resistance Level*	Reference
India	*H. anatolicum*	LPT	Cypermethrin Deltamethrin Diazinon	0.18 – 2.25 1.05 – 4.65 1.82 – 4.46	S – 1	Shyma *et al.*, 2013
	R. microplus		Cypermethrin Deltamethrin Diazinon	0.98 – 3.90 4.50 – 10.80 4.20 – 12.00	S – 2	
	H. anatolicum	LPT	Amitraz Cypermethrin	12.23 3.51	1 2	Singh *et al.*, 2015
	R. microplus	AIT	Cypermethrin Deltamethrin	0.32 – 13.18 0.94 – 51.71	S – 2 S – 4	Godara *et al.*, 2019
	H. anatolicum	LPT	Fipronil	0.23 – 3.80	S – 1	Gupta *et al.*, 2020
	R. microplus			2.40 – 28.20	1 – 3	
	R. microplus	AIT	Cypermethrin Deltamethrin	0.77 – 18.66 0.73 – 22.59	S – 2 S – 2	Solanki *et al.*, 2020
	R. microplus	AIT	Coumaphos Cypermethrin Deltamethrin Diazinon Ivermectin	8.52 – 13.20 7.05 – 13.20 3.40 – 24.02 1.60 – 3.81 0.91 – 9.88	2 2 1 – 2 2 S – 2	Sagar *et al.*, 2020
Pakistan	*H. anatolicum*	AIT	Fipronil Ivermectin	11.12 9.97	2	Kamran *et al.*, 2020
		LIT	Fipronil Ivermectin	13.27 7.78	2	
	R. microplus	LPT	Cypermethrin	0.80 – 17.46	S – 2	Sindhu *et al.*, 2022

*Resistance level based on resistance factor (RF). Susceptible: RF ≤ 1.4; Level 1:1.5 – 5; Level 2: 5.1 – 25; Level 3: 25.1 – 40; Level 4: RF > 40.1.

Challenges and Advancements of *Metarhizium anisopliae* as an Alternative Ticks Control

The relative slow killing speed and inconsistent performance of the entomopathogenic fungus as microbial biocontrol agents are seemingly not something new since the limitations were stated few decades ago in a review paper by Moore & Prior (1993). Many factors can be contributed to the limitations and challenges of adopting the entomopathogenic fungus to control ticks. It is notable that the inconsistence performance is link directly to the short shelf-life of this living organism (Sarma *et al*., 2023). The shelf life of entomopathogenic fungus is an important feature to consider because it increases the microorganism's commercial feasibility (Meirelles *et al*., 2023). It became one of the main obstacles to getting this biological control on the market since under storage, the viability is decreasing (Meirelles *et al*., 2023). Moore & Prior (1993) have stated that the estimated range for MA viability was only range from 3 to 18 months and this has been supported with a study from Sarma *et al*. (2023) that MA could be viable until 180 days but it started to decrease the virulence from day 20 until day 180.

In addition, the diverse strains of MA display variations in their virulence, efficacy, and adaptability to different insect hosts (Hussien *et al*., 2021). Selecting the most suitable strain for mass production and maintaining consistent quality and effectiveness of the produced inoculum can be challenging. It requires careful strain selection, monitoring of genetic stability, and maintaining a repository of well-characterized and high-quality strains. Overcoming these challenges is critical for optimizing the use of MA as an acaricide in the field, requiring a meticulous focus on refining the conidial production process and selecting suitable adjuvants for formulations, ensuring product stability, cost-effectiveness, and efficacy (Barbieri *et al*., 2023). The impediment posed by the high cost of the substrate in MA mass production technology can potentially be mitigated by adopting the alternative approach suggested by Barra-Bucarei *et al*. (2016), advocating for the use of recycled rice substrate from MA production instead of relying on new parboiled rice.

Drawing insights from the information presented in Table 1, a conspicuous gap in research becomes evident, particularly in the absence of *in vivo* studies in Asia that examine the efficacy of MA under field conditions. This research void aligns with observations by Chen *et al.* (2014), who proposed that MA exhibits diminished virulence in field environments compared to laboratory settings due to soil conditions influencing its pathogenicity. The microclimatic sensitivity of this fungus is underscored by its susceptibility to various environmental factors, including soil moisture, air temperature, soil temperatures, air relative humidity, and solar UV radiation (Chen *et al*., 2014; Barbieri *et al*., 2023). Many pest insects dwell in geographic regions with considerable temperature changes; thus, effective biological control agents must not only endure extreme temperatures in these areas but also resume growth during periods of favourable conditions (Keyser *et al*., 2014). To advance MA as a biopesticide, comprehensive field efficacy data is the key, serving as the foundational information for further research and development.

In general, advancements in MA predominantly centre on mass production and formulation, key prerequisites for commercialization and widespread adoption in control programmes. The primary method for large-scale production is solid-state fermentation (SSF), leveraging various grains like rice, wheat, chickpea, pigeon pea, black gram, green gram, groundnut, sorghum, soybean, and maize (Agale *et al*., 2018). SSF is recognized for its efficiency, with different substrates yielding varying conidia counts. Green mass and maize demonstrated the highest conidia counts, while green gram and black gram produced comparatively lower spore yields (Agale *et al*., 2018). Additionally, liquid culture in bioreactors emerges as an alternative method for mass production, offering advantages in scalability, process control, and consistent product quality. Liquid fermentation, as highlighted by Barra-Bucarei *et al*. (2016), facilitates the generation of blastopores and mycelium forms (Riaz *et al*., 2013; Kruger *et al*., 2014). Different media play a pivotal role in this process, with Sabouraud Dextrose Broth exhibiting the highest conidial count, closely followed by Potato Dextrose Broth (Agale *et al*., 2018). The liquid culture approach not only ensures efficiency and precision but also underscores *M. anisopliae*'s adaptability to different fermentation methods, enhancing the versatility of large-scale cultivation practices.

In terms of formulation, in the early stage, the formulations were relatively basic by mixing the conidia with carrier materials like talc or clay. The recent advancements in formulation techniques have been pivotal in enhancing the pathogenicity of this fungus. Conidia formulations emerge as a promising biological tool in effectively managing ticks. Achieving practical formulations necessitates comprehensively considering factors such as the duration of conidia viability, sustained virulence, and the overall efficacy of entomopathogenic fungi when deployed in field conditions. The creation of an appropriate formulation is critical to the successful use of mycoinsecticides. For commercialization to occur, the formulation's biological and physical qualities must be stable for at least a year, preferably for more than 18 months (Daoust & Roberts, 1983; Alvest *et al*., 2002). Crucially, successful formulations must incorporate ingredients that facilitate conidia adherence to the tick surface, ensuring targeted action, alongside elements that protect against adverse environmental conditions. Table 3 summarises 34 papers on some of the formulations of *Metarhizium* that have been tested and used globally. The references used were based on the literature search using the keywords: (metarhizium) AND (biological AND control) AND (formulation OR formulations) with 277 research papers being screened. The search was not restricted by year and arthropod hosts, ensuring a broad scope of inclusion. This approach allows for a comprehensive analysis of the development of formulations over time, providing insights into trends and advancements in formulation improvements across various arthropod hosts and different regions from year to year.

Advancements in *Metarhizium* formulation have been ongoing for three decades, aiming to optimize the practicality of this fungus. Among various types of formulations, oil formulations have gained popularity, as highlighted by data from Table 3. According to Kaaya & Hedimbi (2012), oil formulations outperform water-based ones due to their superior blending with the lipophilic cuticle of ticks. Additionally, oils provide a longer-lasting moisture source for fungus germination compared to water, which evaporates rapidly. Rice *et al*. (2020) further support this idea, suggesting that oil-based emulsions offer advantages over purely aqueous solutions, including enhanced adhesion of conidia to lipophilic insect cuticles and increased persistence of conidia. The choice of oil is crucial, as certain oils can inhibit spore germination, affecting effectiveness, while others may not be compatible with conidia formulations (Seye *et al*., 2012). Hence, selecting the appropriate oil is essential for maximizing the effectiveness of the fungus in mycoinsecticide formulations.

Future Direction and Conclusion

Given recent advancements, the future of *Metarhizium anisopliae* (MA) is promising. Urgent attention is needed to improve MA's pest control efficacy, which is slower than chemical treatments. Enhancing its effectiveness could make it a competitive biopesticide and a sustainable alternative. Understanding how MA interacts with other species will help develop formulations that target pests while minimizing harm to beneficial organisms. For successful incorporation into agriculture, advancements in formulation research, commercial production, regulatory approval, and public awareness are essential. Improving stability, shelf life, and application efficiency is critical to making MA useful and affordable. Streamlining production processes and regulatory assessments, along with educating farmers about acaricide resistance and MA strategies, can reduce reliance on chemical acaricides and promote sustainable alternatives.

Table 3. Different formulations of *Metarhizium* as mycoinsecticides

Formulations	Improvements	Ingredients	References
Alginate formulations	Protect fungi from solar radiation and high-temperature	Sodium alginate + calcium chloride	Pereira & Robert, 1991
Oil formulations	Protect fungi from solar radiation and high-temperature	Cornstarch oil	Pereira & Robert, 1991
	Increase persistence of oil and water formulation of conidia	ShellSol T	Inyang *et al*., 2000
	Increase virulence	Coconut/soybean oil	Batta, 2003
	Increase virulence	Neem oil	Okumu *et al*., 2007
	Increase virulence	Canola oil	Lemon *et al*., 2008
	Increase virulence	Sunflower oil	Brito *et al*., 2008
	Increase virulence and persistence	Neem oil	Paula *et al*., 2019
	Enhance ovicidal activity	Sunflower oil	Albernaz *et al*., 2009
	Increase virulence and persistence	ShellSol T	Bukhari *et al*., 2011
		Ondina oil 917	
	Suppress on-host and off host tick population	Sunflower oil	Kaaya & Hedimbi, 2012
	Increase virulence	Mineral oils	Camargo *et al*., 2012
	Increase virulence	Neem oil	Seye *et al*., 2012
	Increase virulence	Mineral oil	Rodrigues *et al*., 2019
	Increase virulence and persistence	Oil in water	Muniz *et al*., 2020
	Increase virulence	Mineral oil + diatomaceous earth	Barbieri *et al*., 2023
		Silicon oil	
Dust formulations	Increase virulence and persistence Increase virulence and persistence Increase virulence	Talcum Diatomaceous earth Bad wheat flour	Gupta *et al*., 2020 Michalaki *et al.*, 2006 Sharriford *et al*., 2014
Dried-powdered conidia	Better protection Increase virulence	Kaolin	Hendrawan & Ibrahim, 2006
		Tapioca flour	
		Talc	
Fungus mixed with acaricide formulations	Increase virulence	Imidacloprid	Brito *et al*., 2008
	Increase virulence	Amitraz Deltamethrin Pyrethroids Organophosphate Monoterpenoid	Carneiro *et al*., 2022
Aqueous formulations	Suppress on-host and off host tick population	Peanut oil	Kaaya & Hedimbi, 2012
	Enhance ovicidal activity	Vegetable oil	Luz *et al*., 2015
Leaf extract formulation	Increase virulence	*Calpurnia aurea* extract	Nana *et al*., 2016
Encapsulation	Enhance shelf life Increase virulence and persistence Improved survival and shelf life Increase virulence Increase virulence and persistence Enhance shelf life and bioactivity	Microencapsulated Bioencapsulatio Calcium gluconate Calcium-alginate encapsulation Ionic gelation Alginate-based encapsulation	Rodrigues *et al*., 2019 Przyklenk *et al*., 2017 Humbert *et al*., 2017 Shah *et al*., 2022 Meirelles *et al*., 2023 Sarma *et al*., 2023
Air-dried blastospore	Increase virulence	Diatomaceous earth	Iwanicki *et al*., 2018
Granular formulations	Increase virulence Increase virulence	Organic millet Microsclerotia Blastospores-based	Sullivan *et al*., 2021 Marciano *et al*., 2021
Conidial emulsion formulations	Enhance shelf life	Emulsion	Lei *et al*., 2022
Modified atmosphere packaging	Enhance shelf life	Millet grain	Jeong *et al*., 2022

This review explores the potential of *Metarhizium anisopliae* (MA) as a biocontrol agent against ticks and the current state of tick control in Asia. MA is promising for integrated tick management due to its low environmental impact and flexibility. Its use can improve control methods and prevent tick resistance to chemical acaricides. While promising, further studies and field trials are needed to optimize its effectiveness. MA should complement, not replace, chemical control, highlighting its role in integrated tick management. Current literature indicates that livestock ticks in Asia are beginning to develop resistance to acaricides, though resistance levels are still modest. This low level of resistance and the continued effectiveness of acaricides may limit the adoption of alternatives like MA. However, it is crucial to monitor this situation as resistance evolves, and proactive measures will be necessary to ensure sustainable pest management in the future.

ACKNOWLEDGEMENT

We express our gratitude for the support provided by the members of the Faculty of Veterinary Medicine at Universiti Malaysia Kelantan and the Mycology and Pathology Laboratory of the Forest Research Institute Malaysia. We would also want to express our gratitude to the Ministry of Higher Education Malaysia for providing financing for this research.

Funding
The Ministry of Higher Education Malaysia funded this study through the Fundamental Research Grant Scheme (FRGS/1/2022/WAB04/UMK/02/9).

Credit Authorship Contribution Statement
Nurul Fatin Amirah Mohd Azmi: Conceptualization, Writing – original draft. Investigation, Formal analysis. **Lim Chien Yee:** Conceptualization, Investigation, Writing – original draft. **Siew Shean Choong:** Supervision, Writing – Review & editing. **Tan Li Peng:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Samsuddin Ahmad Syazwan:** Validation, Visualization, Writing – review & editing.

Conflict of Interest
The authors declare that they have no conflict of interest.

Data Availability
No data was used for the research described in the article.

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