Eurasia Specialized Veterinary Publication

International Journal of Veterinary Research and Allied Science
ISSN:3062-357X
2021, Volume 1, Issue 1, Page No: 9-18

Available online at: www.esvpub.com/

Synthetic Acaricides in Tick Control Programs: An Overview of Present Applications

K R. Reshma[1]*, K. Prakasan[1]

[1]Postgraduate and Research Department of Zoology, Maharaja's College, Ernakulam, Kerala, India.

***E-mail** ✉ rechu060993@cgmail.com

ABSTRACT

Ticks are a large group of blood-feeding arthropods that act as vectors for a range of pathogens of medical and veterinary importance. Historically, synthetic acaricides have been the cornerstone of global tick control efforts. Consequently, it is essential to develop strategies that help maintain the effectiveness of these chemicals. This paper provides an overview of synthetic acaricides, tracing their use from early applications to current market options. It also examines the mechanisms of action of different acaricide classes, their environmental impact, the challenges posed by resistance in tick populations, the factors contributing to this resistance, and the strategies implemented to increase the effectiveness of existing acaricides.

Keywords: Synthetic acaricides, Mode of action, Acaricide resistance, Resistance management

Received: 02 March 2021
Revised: 12 May 2021
Accepted: 15 May 2021

How to Cite This Article: Reshma KR, Prakasan K. Synthetic Acaricides in Tick Control Programs: An Overview of Present Applications. Int J Vet Res Allied Sci. 2021;1(1):9-18. https://doi.org/10.51847/5qDanSgiSY

Introduction

Ticks are specialized arthropods that are obligate blood-feeders, drawing nourishment from a diverse range of vertebrates worldwide [1, 2]. Known for their significant role in transmitting numerous life-threatening diseases, they also pose considerable challenges as pests for both humans and livestock [3, 4]. Domestic animals, which are particularly vital for rural communities in developing countries, provide essential resources such as income, food, energy, manure, and raw materials [5]. However, tick infestations are a major threat to these animals, causing global losses estimated at between US$ 13.9 and 18.7 billion each year [6]. As a result, tick control became a critical concern in both the public and animal health sectors.

The primary method for controlling ticks has traditionally been the usage of synthetic acaricides, offering a relatively efficient and cost-effective means to manage tick populations during outbreaks. However, prolonged usage of these chemicals has led to the development of resistance in numerous tick species, diminishing their effectiveness [7, 8]. Consequently, it is vital to regularly monitor ticks for resistance to commonly used acaricides to ensure the sustainability of livestock production. This paper explores the various aspects of synthetic acaricides, aiming to enhance the understanding and formulation of strategies to combat resistant tick species.

Results and Discussion

Synthetic acaricides

Before the discovery by Smith and Kilborne of ticks as vectors of *Babesia bigemina* in cattle, chemical agents for tick control were already in use in regions like the United States, Southern Africa, and Australia [9-11]. In the U.S., early methods included applying mixtures of lard and sulfur, fish oil, lard, kerosene, or cotton-seed oil to

cattle's legs and bodies. Other combinations, such as kerosene mixed with cotton-seed oil and sulfur, or crude petroleum with cotton-seed oil, were also used effectively. These treatments were applied 2-3 times a week with syringes, brushes, brooms, sponges, or mops [12, 13]. Meanwhile, in Australia, dipping vats containing oil and "carbolics" were employed by researchers in 1895 to immerse cattle as part of their tick control practices [14].

Arsenicals

Arsenicals were the first acaricides extensively used to manage ticks and tick-borne diseases. Their use in controlling sheep parasites predates their initial use on cattle in Southern Africa and Australia in 1893 and 1895, respectively [15]. Arsenic-based solutions were recognized for their affordability, stability, and water solubility [16], making them both economical and highly effective [17]. These solutions were particularly utilized in controlling Boophilus tick species in countries such as South Africa, Australia, Brazil, Argentina, Colombia, Kenya, and Zambia [17].

However, after a few years, instances of field failures began to emerge. The first signs of arsenic resistance in Australia were observed in *Boophilus microplus* in 1937. Similar cases of resistance were reported in South Africa in species such as *Boophilus decoloratus*, *Amblyomma hebraeum*, *Hyalomma rufipes*, *H. truncatum*, *Rhipicephalus appendiculatus*, and *Rhipicephalus evertsi* [18]. As no alternative acaricides were available, tick infestations on cattle surged significantly worldwide. The development of resistance to arsenicals, along with the narrow margin between effective and toxic concentrations for both ticks and cattle, along with concerns over toxic residues in animal tissues, led to the eventual replacement of arsenic by synthetic organic insecticides following World War II [19].

Organochlorines

Organochlorines were the first synthetic organic insecticides introduced for tick control in cattle. These compounds offered broad-spectrum activity, high efficiency, and long-lasting residual effects. Compared to arsenic-based acaricides, they were also less toxic and more cost-effective [20]. Among the most notable organochlorines were benzene hexachloride [16] and DDT [21-23]. The widely used chemicals in this category included dieldrin, aldrin, cyclodiene compounds, and toxaphene, a polychloroterpene product [18]. The substances functioned by binding to the picrotoxinin site within the γ-aminobutyric acid (GABA) chloride ionophore complex [24, 25], disrupting chloride ion flow into neurons [26, 27]. This interference impaired the GABA-ergic inhibitory neurons, leading to excessive neural excitation and ultimately causing tick mortality.

The first recorded case of organochlorine resistance in *B. microplus* occurred in Brazil in 1952 [28]. The emergence of cross-resistance among different tick species, including *B. microplus*, *Boophilus decoloratus*, and *R. appendiculatus*, significantly reduced the effectiveness of these chemicals [18]. This resistance issue led to a decline in their use across regions such as Australia [29, 30] and parts of Equatorial and Southern Africa [31, 32]. By 1962, nearly all organochlorines were banned for tick control due to their persistent residues in meat, milk, and the environment, as they exhibited poor biodegradability and strong lipid affinity [33]. However, recent in vitro studies on lindane's effects on engorged female *Rhipicephalus (Boophilus) annulatus* and *Haemaphysalis bispinosa* demonstrated its efficacy as an acaricide. Despite causing high mortality, reduced fecundity, and hindrance in egg hatching, its use remains prohibited in India [34].

Organophosphates and carbamates

With the rise of resistance in tick species against organochlorines, a new category of organic insecticides, known as organophosphates, was developed. These compounds were initially examined for their pesticidal properties in the 1930s based on their effects on the nervous system. The first organophosphate, parathion, was introduced in the 1940s, and by the mid-1950s, organophosphates gradually replaced organochlorines in South America as tick populations became resistant to the latter [33, 35]. Unlike organochlorines, which were highly persistent in the environment, organophosphates were chemically unstable and degraded more quickly. However, they posed a higher risk of acute toxicity to livestock [16]. These acaricides were specifically designed to combat organochlorine-resistant *Boophilus* ticks, which were widespread in cattle-rearing regions across the tropics and subtropics [36]. In Australia, organophosphates were the dominant tick control agents from the 1950s until the late 1960s and early 1970s. Similarly, Mexico’s national tick eradication program (1974–1984) relied heavily on organophosphates [37]. During this period, the most commonly used compounds included coumaphos, chlorpyriphos, diazinon, chlorfenvinphos, and ethion.

Alongside organophosphates, another class of chemicals known as carbamates was introduced in the mid-1950s. These compounds, which were esters of carbamic acid, closely resembled organophosphates in their mode of action [38]. Both groups of acaricides, including examples like carbaryl and promacyl, functioned by inhibiting AChE, an enzyme essential for nervous system function [18, 39-41]. When ticks were exposed to cholinesterase inhibitors, the enzyme could no longer break down acetylcholine, leading to continuous neural stimulation, overexcitation of the nervous system, and ultimately, tick mortality [42]. However, compared to organophosphates, carbamates were more toxic to mammals and significantly more expensive [17].

Despite their initial effectiveness, the widespread reliance on organophosphate-carbamate acaricides eventually led to resistance in multiple tick species. The first reports of resistance in *B. microplus* appeared in Australia during the mid-1960s [43]. Soon after, resistance to this class of chemicals was documented in several other species, including *B. decoloratus*, *A. hebraeum*, *R. appendiculatus*, and *Rhipicephalus evertsi* in South Africa. Resistant strains of *B. microplus* were later reported in Brazil, South America, Mexico, Colombia, Uruguay, Argentina, and Venezuela [18]. As a result, the use of organophosphates declined across North America and European Union nations during the 1970s [44]. A similar reduction occurred in Australia, large parts of Africa, and various Latin American regions [45]. Nevertheless, certain organophosphates continue to be used in veterinary and public health applications due to their targeted efficacy. For instance, coumaphos remains a key active ingredient in the acaricide officially sanctioned by the U.S. Cattle Fever Tick Eradication Program for livestock treatment [46].

Formamidines

By the mid-1970s, as the organophosphate-carbamate group of acaricides failed to effectively control tick populations, they were replaced by amidines [47]. This category included compounds such as chlordimeform, clenpyrin, amitraz, chloromethiuron, and cymiazole [48]. In Australia, chlordimeform was initially introduced as a supplement to organophosphates in cattle dipping vats to restore their effectiveness against resistant tick strains [47]. However, due to concerns over its carcinogenic properties, it was withdrawn from the market in 1976 [49]. Among the chemicals in this class, amitraz, a triazapentadiene compound, became the primary active ingredient widely used for tick control in livestock and dogs [44]. Amitraz acted as an octopamine agonist, disrupting the nervous system of arachnids and leading to their demise [50].

Commercially available amitraz formulations proved effective against organophosphate-resistant *B. microplus* and were widely adopted in Australia during the mid-1970s for cattle treatment [18, 51]. Extensive trials conducted in South Africa over five years confirmed amitraz's effectiveness in managing *B. decoloratus*, *R. appendiculatus*, *R. evertsi*, and *A. hebraeum* populations [52]. However, resistance to amitraz began emerging 4-10 years after its introduction, with the first documented cases appearing in Australia in the early 1980s [47]. Subsequent reports of resistance surfaced from Mexico, South America, New Caledonia, South Africa, Brazil, and Colombia [18]. Despite these challenges, Jonsson and Hope [53] highlighted that amitraz remained one of the most commonly used acaricides for tick control in regions such as Australia, Latin America, and Southern Africa [54].

Pyrethroids

Pyrethroids emerged in the late 1970s as a solution for tick populations resistant to amidines. These synthetic compounds were developed as stable alternatives to natural pyrethrum, which degraded quickly in sunlight. Though research on pyrethroids began in 1949, the third-generation chemicals, permethrin and fenvalerate, were the first to be widely used for tick control. In the 1970s, the US Environmental Protection Agency (EPA) approved permethrin and deltamethrin as acaricides. Other widely used pyrethroids include cypermethrin, flumethrin, cyhalothrin, and cyfluthrin [55, 56]. They disrupted sodium ion channels in nerve membranes, leading to nerve excitation and paralysis in ticks [42, 57, 58].

By the early 2000s, pyrethroids made up 17% of the global insecticide market [59]. Flumethrin proved particularly effective at lower concentrations compared to other pyrethroids [60]. Studies showed that trans-flumethrin was significantly more toxic to *B. microplus* than cis-cypermethrin and deltamethrin [61]. Although pyrethroids had lower toxicity to mammals and birds, their widespread use led to environmental concerns due to urban runoff, which posed risks to aquatic organisms.

Macrocyclic lactones

Introduced in 1981, macrocyclic lactones offered a long-lasting and effective tick control method [62]. These compounds had greater residual activity than synthetic pyrethroids and targeted a broad range of arthropods and nematodes [55]. Macrocyclic lactones fell into two categories: avermectins, derived from *Streptomyces avermitilis*, and milbemycins, obtained from *Streptomyces hygroscopicus aureolacrimosus* [63]. Key acaricides in this group included ivermectin, eprinomectin, doramectin, and moxidectin.

These chemicals worked by increasing gamma-aminobutyric acid (GABA) release, which blocked nerve and muscle function in ticks, ultimately causing paralysis and death [64-66]. Subcutaneous treatments with ivermectin, doramectin, and moxidectin effectively controlled *B. microplus* infestations in cattle. However, their high cost restricted widespread use [67-69]. The first report of macrocyclic lactone resistance in *B. microplus* came from Brazil in the early 2000s [18].

Phenylpyrazoles

Discovered in the 1980s, fipronil was the first acaricide in the phenylpyrazole class, initially developed for crop protection. Later, it was tested as a pour-on treatment for cattle infested with *B. microplus*. In controlled environments, a single application provided over 99% efficacy and protected against larval reinfestation for up to eight weeks [70]. However, under field conditions, factors like sunlight and weather exposure reduced its long-lasting effects by two to three weeks [71]. While fipronil is used in several Latin American countries for tick control, it has not been registered for use on food animals in the United States and some other regions.

Benzoylphenylurea

Diflubenzuron was the first benzoyl phenyl urea acaricide, approved in Brazil as an oral treatment for *Rhipicephalus (Boophilus) microplus* infestations. Most compounds in this group, including diflubenzuron, lufenuron, and flufenoxuron, were effective against various insects. However, fluazuron stood out due to its high efficacy against ticks and some mite species [55]. Marketed as a tick development inhibitor, fluazuron was available as a pour-on formulation, offering long-term protection against *R. microplus* [72]. It significantly reduced the reproductive capacity of engorged female ticks and increased immature tick mortality by disrupting molting. The effects of fluazuron lasted around twelve weeks. Because of its strong fat-binding properties, it was excreted in milk, making treatment unnecessary for suckling calves. Due to its persistence in fat, a six-week withdrawal period was required before treated cattle could be used for human consumption [72].

Spinosad

Spinosad belongs to the spinosyn class of pesticides, which are tetracyclic-macrolide compounds derived from the fermentation of soil bacteria in the *Saccharopolyspora* genus [73, 74]. Its mode of action involves interfering with acetylcholine binding at nicotine acetylcholine receptors in the postsynaptic cell [49]. As a systemic acaricide, spinosad has been effectively used as an oral treatment in dogs to manage *Rhipicephalus sanguineus* infestations [75]. Research on its efficacy against both hard and soft ticks highlights its potential as an alternative to conventional acaricides used for vector and pest control in public health [76]. Spinosad demonstrated around 90% effectiveness in controlling *B. microplus* on cattle across all three parasitic stages at the time of treatment. Nymphs and larvae were particularly susceptible compared to adult ticks [77]. Given its distinct mechanism of action, spinosad offers a viable alternative for managing *B. microplus* populations resistant to other acaricides [18].

Resistance management strategies

Chemical acaricides remain the primary method for tick control, but their effectiveness has declined over time [78]. The widespread and uncontrolled use of these chemicals, errors in solution preparation, improper application techniques, incorrect timing, and poor parasite management have all contributed to the emergence of resistance among tick populations commonly targeted by cattle producers [79]. While completely preventing resistance in tick control programs is unrealistic, certain strategies can help slow its development. Additionally, alternative approaches may be considered when resistance renders specific acaricides ineffective [80].

Application practices

Selecting an appropriate acaricide requires a thorough understanding of the tick species present in the affected area and their resistance to different chemicals. Factors such as application method [81], dosage, frequency, and

treatment timing [82] should be carefully considered to slow resistance development. Frequent use of acaricides accelerates resistance, and earlier research by Jonsson *et al*. [81] and Thullner *et al*. [83] advised limiting applications to no more than five times per season. Additionally, Sun *et al*. [84] recommended confirming field resistance through laboratory testing alongside established management practices.

Rotation of acaricides

Alternating acaricides with different mechanisms of action can help mitigate resistance development [42]. Prolonged use of a single acaricide leads to the dominance of resistant alleles, eventually causing treatment failure [44]. In a laboratory study by Thullner *et al*. [83], a highly deltamethrin-resistant R. microplus strain showed reduced resistance when deltamethrin was rotated with coumaphos. Similarly, Jonsson *et al*. [85] observed a decline in amitraz resistance when cattle were treated alternately with spinosad and amitraz. However, further field research is necessary to confirm the effectiveness of this approach.

Using acaricide combinations

Using combinations of acaricides with different modes of action reduces the likelihood of resistance developing against both chemicals [86]. This strategy has been implemented in several countries. In Australia, organophosphate-synthetic pyrethroid combinations, including deltamethrin + ethion and cypermethrin + chlorfenvinphos, have remained available [18]. Similarly, in Brazil, cypermethrin + chlorfenvinphos and permethrin + dichlorvos have been commonly used [87]. In Mexico, cymiazole + cypermethrin is a widely applied mixture [88]. Recent findings by Santana [89] demonstrated that cypermethrin (15%) + chlorpyrifos (25%) + citronellal (1%) was more effective against *Rhipicephalus (Boophilus) microplus* than pyrethroids or organophosphates alone.

Use of synergists

Certain acaricides exhibit synergistic effects when combined. Piperonyl butoxide has been used alongside pyrethroids to enhance their efficacy against resistant tick populations. Li *et al*. [90] observed synergy between permethrin and amitraz, while Fernandez-Salas *et al*. [91] found that combining amitraz with permethrin effectively controlled a pyrethroid-resistant R. microplus strain in Mexico. However, these combinations must be carefully formulated and applied at recommended concentrations to ensure compatibility and persistence [42].

Tick pheromones in combination with acaricides

Ticks respond to semiochemicals that influence behaviors such as aggregation, attachment, and mating. Exploiting these pheromones in control strategies could enhance acaricide effectiveness [92, 93]. While pheromones alone are insufficient for tick management, their combination with acaricides—ideally in a slow-release delivery system—could improve results. Technologies such as embedding pheromones in plastic, adhesives, paraffin, or gelatin microcapsules enable gradual release. A field study using assembly pheromone + toxaphene effectively controlled *A. hebraeum* [94]. Sonenshine *et al*. [95] reported high *Dermacentor variabilis* mortality when propoxur was combined with the sex pheromone 2,6-dichlorophenol on dogs, while Sonenshine *et al*. [96] found that Ixodes scapularis treated with permethrin and an arrestant pheromone showed 95% mortality in laboratory tests. Combining pheromones with acaricides could improve treatment efficiency and reduce the impact on non-target species.

Conclusion

Ticks and the diseases they transmit pose a significant risk to both human and animal health worldwide. Managing tick populations has become a top priority for public and veterinary health systems, with acaricides serving as a key tool in effective control strategies. During sudden outbreaks, chemical acaricides remain the primary solution due to their rapid and efficient action. However, concerns related to resistance development, the need for safer formulations, and their environmental impact are influencing how these chemicals are used. History has shown that resistance to acaricides is inevitable, making long-term tick control dependent on continuous research and innovation. Future efforts must focus on developing novel, lower-risk acaricides and implementing integrated management strategies to ensure sustainable control.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

References

1. Lakshmi T, Rajendran R, Ezhilarasan D, Silvester A. Highperformance liquid chromatography and tandem mass spectrometric analysis of beta ecdysone from Achyranthes aspera extract: an antimalarial drug. J Adv Pharm Educ Res. 2018;7(2):61-5.
2. Allam NA, El Moghazy FM, Abdel-Baky SM. Molecular epidemiological updates on spotted fever rickettsioses in animal species and their hard ticks settling Egyptian desert. J Adv Pharm Educ Res. 2018;8(1):64-74.
3. Keirans JE, Durden LA. Tick systematics and identification. In: Goodman JL, Dennis DT, Sonenshine DE, eds. Tick-borne Diseases of Humans. ASM Press, Washington, D.C. 2005. p. 123-40. doi:10.1128/9781555816490.ch7
4. Yazdi SH, Vosoogh A. Mini review on heavy metals in groundwater; pollution and removal. J Biochem Tech. 2019;2:149-64.
5. Alqahtani AN, Alanazy SH, Aljameel OS, Aldhawi FS, Jamjoom MM, Al Sharhan AH, et al. Evaluation of diagnosis and management of anaphylactic shock in emergency room: a literature review. Int J Pharm Res. Allied Sci. 2020;9(1):93-8.
6. Prakasan K. Tick parasites of man and domestic animals from Kerala. Invertebr Syst Biol. 2014:63-6.
7. Jongejan F, Uilenberg G. The global importance of ticks. Parasitology. 2004;129:S3-S14.
8. De Castro JJ. Sustainable tick and tickborne disease control in livestock improvement in developing countries. Vet Parasitol. 1997;71(2-3):77-97. doi:10.1016/S0304-4017(97)00033-2
9. Harris RL, George JE, Ahrens EH, Davey RB, Bazan HO. Selection for resistance to coumaphos in a strain of southern cattle tick (Acari: Ixodidae). J Econ Entomol. 1988;81(2):545-8. doi:10.1093/jee/81.2.545
10. Raynal JT, Silva AA, Sousa TD, Bahiense TC, Meyer R, Portela RW. Acaricides efficiency on Rhipicephalus (Boophilus) microplus from Bahia state North-Central region. Rev Bras Parasitol Vet. 2013;22(1):71-7. doi:10.1590/S1984-29612013005000006
11. Smith T, Kilborne FL. Investigations into the nature, causation, and prevention of Texas or southern cattle fever. US Department of Agriculture, Bureau of Animal Industry; 1893.
12. Francis M, Cooper C. Preventive measures for farm or range use. Bull Texas Agric Exp Sta. 1892;24:253-6.
13. Mohler JR. Texas or tick fever and its prevention. US Department of Agriculture; 1906.
14. Angus BM. The history of the cattle tick Boophilus microplus in Australia and achievements in its control. Int J Parasitol. 1996;26(12):1341-55. doi:10.1016/S0020-7519(96)00112-9
15. Shaw RD. Tick control on domestic animals. 1. A brief history of economic significance of tick infestations. Trop Sci. 1969;11(2):113.
16. Drummond RO. Tick-borne livestock diseases and their vectors. 4. Chemical control of ticks. World Anim Rev. 1976;19:28-33.
17. Rajput ZI, Hu SH, Chen WJ, Arijo AG, Xiao CW. Importance of ticks and their chemical and immunological control in livestock. J Zhejiang Univ Sci B. 2006;7(11):912-21. doi:10.1631/jzus.2006.B0912
18. George JE, Pound JM, Davey RB. Chemical control of ticks on cattle and the resistance of these parasites to acaricides. Parasitology. 2004;129:S353-66.
19. Graham OH, Hourrigan JL. Eradication programs for the arthropod parasites of live stock. J Med Entomol. 1977;13(6):629-58. doi:10.1093/jmedent/13.6.629
20. Yessinou RE, Akpo Y, Adoligbe C, Adinci J, Assogba MN, Koutinhouin B, et al. Resistance of tick Rhipicephalus microplus to acaricides and control strategies. J Entomol Zool Stud. 2016;4(6):408-14.

21. Cobbett NG. Preliminary tests in Mexico with DDT, cube, hexachlorocyclohexane (benzene hexachloride) and combinations thereof, for the control of the cattle fever tick, Boophilus annulatus. Am J Vet Res. 1947;8(28):280.
22. Maunder JC. Cattle tick control: results achieved in the field with DDT and BHC. Qld Agric J. 1949:1-8.
23. Whitnall AB, McHardy WM, Whitehead GB, Meerholz F. Some observations on the control of the bont tick, Amblyomma hebraeum Koch. Bull Entomol Res. 1951;41(3):577-91. doi:10.1017/S0007485300027838
24. Lawrence LJ, Casida JE. Stereospecific action of pyrethroid insecticides on the gamma-aminobutyric acid receptor-ionophore complex. Science. 1983;221(4618):1399-401. doi:10.1126/science.6310756
25. Hope M, Menzies M, Kemp D. Identification of a dieldrin resistance-associated mutation in Rhipicephalus (Boophilus) microplus (Acari: Ixodidae). J Econ Entomol. 2010;103(4):1355-9. doi:10.1603/EC09267
26. Bloomquist JR, Soderlund DM. Neurotoxic insecticides inhibit GABA-dependent chloride uptake by mouse brain vesicles. Biochem Biophys Res Commun. 1985;133(1):37-43. doi:10.1016/0006-291X(85)91838-8
27. Corley SW, Piper EK, Jonsson NN. Generation of full-length cDNAs for eight putative GPCnR from the cattle tick, R. microplus using a targeted degenerate PCR and sequencing strategy. PLoS One. 2012;7(3). doi:10.1371/journal.pone.0032 480
28. Freire JJ. Arseno e cloro resistência e emprego de tiofosfato de dietilparanitrofenila (Parathion) na luta anticarrapato Boophilus microplus (Canestrini, 1887). Bol Dir Prod Anim. 1953;9(17):3-21.
29. Norris KR, Stone BF. Toxaphene-resistant cattle ticks (Boophilus microplus (Canestrini)) occurring in Queensland. Aust J Agric Res. 1956;7(3):211-26. doi:10.1071/AR9560211
30. Stone BF, Meyers RA. Dieldrin-resistant cattle ticks, Boophilus microplus (Canestrini) in Queensland. Aust J Agric Res. 1957;8(3):312-7. doi:10.1071/AR9570312
31. Whitehead GB. Acaricide resistance in the blue tick, Boophilus decoloratus (Koch).— Part I. Bull Entomol Res. 1958;49(4):661-73. doi:10.1017/S0007485300053 943
32. Baker JA, Shaw RD. Toxaphene and lindane resistance in Rhipicephalus appendiculatus, the brown ear tick of equatorial and southern Africa. J South Afr Vet Assoc. 1965;36(3):321-30.
33. Graf JF, Gogolewski R, Leach-Bing N, Sabatini GA, Molento MB, Bordin EL, et al. Tick control: an industry point of view. Parasitology. 2004;129(S1):S427-42. doi:10.1017/S0031182004006 079
34. Ravindran R, Jyothimol G, Amithamol KK, Sunil AR, Chandrasekhar L, Lenka DR, et al. In vitro efficacy of amitraz, coumaphos, deltamethrin and lindane against engorged female Rhipicephalus (Boophilus) annulatus and Haemaphysalis bispinosa ticks. Exp Appl Acarol. 2018;75(2):241-53. doi:10.1007/s10493-018-0262-y
35. Shanahan GJ, Hart RJ. Change in response of Lucilia cuprina Wied. to organophosphorus insecticides in Australia. Nature. 1966;212(5069):1466-7.
36. Shaw RD. Tick control on domestic animals. II. The effect of modern methods of treatment. Trop Sci. 1970;12:29-36.
37. Trapapa BJ. The campaign against Boophilus microplus in Mexico, benefit, problems and prospects. Animal production and health. Food and Agricultural Organization: Mexico; 1989. p. 50-75.
38. Spickett AM. Acaricides and resistance. Vet Ectoparasitol Protozool. 1998;1:1-3.
39. Faza AP, Pinto IS, Fonseca I, Antunes GR, de Oliveira Monteiro CM, Daemon E, et al. A new approach to characterization of the resistance of populations of Rhipicephalus microplus (Acari: Ixodidae) to organophosphate and pyrethroid in the state of Minas Gerais, Brazil. Exp Parasitol. 2013;134(4):519-23. doi:10.1016/j.exppara.2013.04.06
40. Temeyer KB, Olafson PU, Brake DK, Tuckow AP, Li AY, de León AA. Acetylcholinesterase of Rhipicephalus (Boophilus) microplus and Phlebotomus papatasi: gene identification, expression, and biochemical properties of recombinant proteins. Pestic Biochem Physiol. 2013;106(3):118-23. doi:10.1016/j.pestbp.2013.01.005
41. Temeyer KB, Tuckow AP, Brake DK, Li AY, de León AA. Acetylcholinesterases of blood-feeding flies and ticks. Chem Biol Interac. 2013;203(1):319-22. doi:10.1016/j.cbi.2012.09.010
42. Abbas RZ, Zaman MA, Colwell DD, Gilleard J, Iqbal Z. Acaricide resistance in cattle ticks and approaches to its management: the state of play. Vet Parasitol. 2014;203(1-2):6-20. doi:10.1016/j.vetpar.2014.03.006
43. Roulston WJ, Stone BF, Wilson JT, White LI. Chemical control of an organophosphorus- and carbamate-resistant strain of Boophilus microplus (Can.) from Queensland. Bull Entomol Res. 1968;58(2):379-92. doi:10.1017/S0007485300056 90X

44. Sonenshine DE, Roe RM, editors. Biology of ticks volume 2. Oxford University Press; 2013. p. 353-74.
45. Kunz SE, Kemp DH. Insecticides and acaricides: resistance and environmental impact. Rev Sci Tech Off Int Epizoot. 1994;13(4):1249-86.
46. Miller RJ, Li AY, Tijerina M, Davey RB, George JE. Differential response to diazinon and coumaphos in a strain of Boophilus microplus (Acari: Ixodidae) collected in Mexico. J Med Entomol. 2008;45(5):905-11. doi:10.1093/jmedent/45.5.905
47. Nolan J. Current developments in resistance to amidine and pyrethroid tickicides in Australia. In: Whitehead GB, Gibson JD, eds. Tick biology and control: proceedings of an International Conference January 27-29, 1981. Grahamstown, South Africa: Tick Research Unit, Rhodes University; 1981.
48. Hollingworth RM. Chemistry, biological activity, and uses of formamidine pesticides. Environ Health Perspect. 1976;14:57-69. doi:10.1289/ehp.761457
49. Ware GW, Whitacre DM. An introduction to insecticides. Pestic Book. 2004;6.
50. Chen AC, He H, Davey RB. Mutations in a putative octopamine receptor gene in amitraz-resistant cattle ticks. Vet Parasitol. 2007;148(3-4):379-83. doi:10.1016/j.vetpar.2007.06.0 26
51. Waltisbuhl D, Farnsworth B, Kemp D. Pesticides used against ectoparasites (ticks, flies, lice) of cattle in Australia. In: Holdsworth PA, ed. Ectoparasiticide use in contemporary Australian livestock production, Avcare Limited: Canberra; 2005. p. 45-57.
52. Stanford GD, Baker JA, Ratley CV, Taylor RJ. Development of a stabilized amitraz cattle dip for control of single and multi-host ticks and their resistant strains in South Africa. In: Whitehead GB, Gibson JD, eds. Tick biology and control: Proceedings of an International Conference January 27-29, 1981. Grahamstown, South Africa: Tick Research Unit, Rhodes University; 1981. p. 143-50.
53. Jonsson NN, Hope M. Progress in the epidemiology and diagnosis of amitraz resistance in the cattle tick Boophilus microplus. Vet Parasitol. 2007;146(3-4):193-8. doi:10.1016/j.vetpar.2007.03.0 06
54. Lovis L, Guerrero FD, Miller RJ, Bodine DM, Betschart B, Sager H. Distribution patterns of three sodium channel mutations associated with pyrethroid resistance in Rhipicephalus (Boophilus) microplus populations from North and South America, South Africa and Australia. Int J Parasitol Drugs Drug Resist. 2012;2:216-24. doi:10.1016/j.ijpddr.2012.08.0 01
55. Taylor MA. Recent developments in ectoparasiticides. Vet J. 2001;161(3):253-68.
56. Ginsberg HS, Faulde, MK. Ticks. Public Health Significance of Urban Pests. Copenhagen, World Health Organ. 2008:303-45.
57. Narahashi T. Mode of action of pyrethroids. Bull World Health Organ. 1971;44(1-2-3):337.
58. Weston DP, Poynton HC, Wellborn GA, Lydy MJ, Blalock BJ, Sepulveda MS, et al. Multiple origins of pyrethroid insecticide resistance across the species complex of a nontarget aquatic crustacean, Hyalella azteca. Proc Natl Acad Sci. 2013;110(41):16532-7.
59. Davies TG, Field LM, Usherwood PN, Williamson MS. DDT, pyrethrins, pyrethroids and insect sodium channels. IUBMB Life. 2007;59(3):151-62. doi:10.1080/15216540701352042
60. Stendel W. Experimental studies on the tickicidal effect of Bayticol pour-on. Vet Med Rev. 1985:99-111.
61. Schnitzerling HJ, Nolan J, Hughes S. Toxicology and metabolism of isomers of flumethrin in larvae of pyrethroid-susceptible and resistant strains of the cattle tick Boophilus microplus (Acari: Ixodidae). Exp Appl Acarol. 1989;6(1):47-54. doi:10.1007/BF01193232
62. Geary TG. Ivermectin 20 years on: maturation of a wonder drug. Trends Parasitol. 2005;21(11):530-2. doi:10.1016/j.pt.2005.08.014
63. Lasota JA, Dybas RA. Avermectins, a novel class of compounds: implications for use in arthropod pest control. Ann Rev Entomol. 1991;36(1):91-117. doi:10.1146/annurev.en.36.010191.000515
64. Bloomquist JR. Ion channels as targets for insecticides. Ann Rev Entomol. 1996;41(1):163-90. doi:10.1146/annurev.en.41.010 196.001115
65. Bloomquist JR. Chloride channels as tools for developing selective insecticides. Arch Insect Biochem Physiol. 2003;54(4):145-56. doi:10.1002/arch.10112
66. Martin RJ, Buxton SK, Neveu C, Charvet CL, Robertson AP. Emodepside and SL0-1 potassium channels: a review. Exp Parasitol. 2012;132(1):40-6. doi:10.1016/j.exppara.2011.08.012
67. Muniz RA, Coronado A, Anziani OS, Sanavria A, Moreno J, Errecalde J, et al. Efficacy of injectable doramectin in the protection of castrated cattle against field infestations of Cochliomyia hominivorax. Vet Parasitol. 1995;58(4):327-33. doi:10.1016/0304-4017(94)00730-Z

68. Davey RB, George JE. Efficacy of macrocyclic lactone endectocides against Boophilus microplus (Acari: Ixodidae) infested cattle using different pour-on application treatment regimes. J Med Entomol. 2002;39(5):763-9. doi:10.1603/0022-2585-39.5.763
69. Kemp DH, McKenna RV, Thullner R, Willadsen P. Strategies for tick control in a world of acaricide resistance. In: Proceedings of the IV Seminario Internacional de Parasitologia Animal; 1999. p. 1-10.
70. Davey RB, Ahrens EH, George JE, Hunter III JS, Jeannin P. Therapeutic and persistent efficacy of fipronil against Boophilus microplus (Acari: Ixodidae) on cattle. Vet Parasitol. 1998;74(2-4):261-76. doi:10.1016/S0304-4017(97)00152-0
71. Davey RB, George JE, Hunter JS, Jeannin P. Evaluation of a pour-on formulation of fipronil against Boophilus annulatus (Acari: Ixodidae) under natural South Texas field conditions. Exp Appl Acarol. 1999;23(4):351-64. doi:10.1023/A:1006183419301
72. Bull MS, Swindale S, Overend D, Hess EA. Suppression of Boophilus microplus populations with fluazuronan acarine growth regulator. Aust Vet J. 1996;74(6):468-70. doi:10.1111/j.1751-0813.1996.tb07575.x
73. Mertz FP, Yao RC. Saccharopolyspora spinosa sp. nov. isolated from soil collected in a sugar mill rum still. Int J Syst Evol Microbiol. 1990;40(1):34-9. doi:10.1099/00207713-40-1-34
74. Lewer P, Hahn DR, Karr LL, Duebelbeis DO, Gilbert JR, Crouse GD, et al. Discovery of the butenyl-spinosyn insecticides: novel macrolides from the new bacterial strain Saccharopolyspora pogona. Bioorg Med Chem. 2009;17(12):4185-96. doi:10.1016/j.bmc.2009.02.035
75. Snyder DE, Cruthers LR, Slone RL. Preliminary study on the acaricidal efficacy of spinosad administered orally to dogs infested with the brown dog tick, Rhipicephalus sanguineus (Latreille, 1806) (Acari: Ixodidae). Vet Parasitol. 2009;166(1-2):131-5. doi:10.1016/j.vetpar.2009.07.046
76. Cetin H, Cilek JE, Oz E, Aydin L, Deveci O, Yanikoglu A. Comparative efficacy of spinosad with conventional acaricides against hard and soft tick populations from Antalya, Turkey. Vet Parasitol. 2009;163(1-2):101-4. doi:10.1016/j/vetpar.2009.04.024
77. Davey RB, George JE, Snyder DE. Efficacy of a single whole-body spray treatment of spinosad, against Boophilus microplus (Acari: Ixodidae) on cattle. Vet Parasitol. 2001;99(1):41-52. doi:10.1016/S0304-4017(01)00456-3
78. Grisi L, Massard CL, Moya Borja GE, Pereira JB. Impacto econômico das principais ectoparasitoses em bovinos no Brasil. Hora Vet. 2002;21(125):8-10.
79. Furlong J, Martins JR, Prata MC. The tick of cattle and resistance: we have to celebrate. Hora Vet. 2007;27:1-7.
80. Nolan J. Acaricide resistance in single and multi-host ticks and strategies for control. Parassitologia (Roma). 1990;32(1):145-53.
81. Jonsson NN, Mayer DG, Green PE. Possible risk factors on Queensland dairy farms for acaricide resistance in cattle tick (Boophilus microplus). Vet Parasitol. 2000;88(1-2):79-92. doi:10.1016/S0304-4017(99)00189-2
82. Sutherst RW, Comins HN. The management of acaricide resistance in the cattle tick, Boophilus microplus (Canestrini) (Acari: Ixodidae), in Australia. Bull Entomol Res. 1979;69(3):519-37. doi:10.1017/S0007485300019015
83. Thullner F, Willadsen P, Kemp D. Acaricide rotation strategy for managing resistance in the tick Rhipicephalus (Boophilus) microplus (Acarina: Ixodidae): laboratory experiment with a field strain from Costa Rica. J Med Entomol. 2007;44(5):817-21. doi:10.1093/jmedent/44.5.817
84. Sun M, Ren Q, Guan G, Liu Z, Ma M, Gou H, et al. Virulence of Beauveria bassiana, Metarhizium anisopliae and Paecilomyces lilacinus to the engorged female Hyalomma anatolicum anatolicum tick (Acari: Ixodidae). Vet Parasitol. 2011;180(3-4):389-93. doi:10.1016/j.vetpar.2011.03.027
85. Jonsson NN, Miller RJ, Kemp DH, Knowles A, Ardila AE, Verrall RG, et al. Rotation of treatments between spinosad and amitraz for the control of Rhipicephalus (Boophilus) microplus populations with amitraz resistance. Vet Parasitol. 2010;169(1-2):157-64. doi:10.1016/j.vetpar.2009.12.026
86. Lovis L, Reggi J, Berggoetz M, Betschart B, Sager H. Determination of acaricide resistance in Rhipicephalus (Boophilus) microplus (Acari: Ixodidae) field populations of Argentina, South Africa, and Australia with the larval tarsal test. J Med Entomol. 2013;50(2):326-35. doi:10.1603/ME12127

87. Furlong J. Diagnosis of the susceptibility of the cattle tick, Boophilus microplus, to acaricides in Minas Gerais state, Brazil. In4. Seminario Internacional de Parasitología Animal, Puerto Vallarta, Jalisco (México); 1999. p. 20-2.
88. Rodriguez-Vivas RI, Alonso-Díaz MA, Rodríguez-Arevalo F, Fragoso-Sanchez H, Santamaria VM, Rosario-Cruz R. Prevalence and potential risk factors for organophosphate and pyrethroid resistance in Boophilus microplus ticks on cattle ranches from the State of Yucatan, Mexico. Vet Parasitol. 2006;136(3-4):335-42. doi:10.1016/j.vetpar.2005.05.0 69
89. Santana LF, de Carvalho Júnior RA, Moreira ÉF, Rodrigues EA, Parreira Filho JM, Freitas BB, et al. Regional study of action in vitro of commercial acaricides on the cattle tick. Rev Inova Ciênc Tecnol/Innov Sci Technol J. 2019;5(2):51-5.
90. Li AY, Chen AC, Miller RJ, Davey RB, George JE. Acaricide resistance and synergism between permethrin and amitraz against susceptible and resistant strains of Boophilus microplus (Acari: Ixodidae). Pest Manag Sci. 2007;63(9):882-9. doi:10.1002/ps.1417
91. Fernández-Salas A, Rodríguez-Vivas RI, Alonso-Díaz MÁ. Resistance of Rhipicephalus microplus to amitraz and cypermethrin in tropical cattle farms in Veracruz, Mexico. J Parasitol. 2012;98(5):1010-4. doi:10.1645/GE-3074.1
92. Sonenshine DE. Pheromones and other semiochemicals of ticks and their use in tick control. Parasitology. 2004;129(S1):S405.
93. Sonenshine DE. Tick pheromones and their use in tick control. Annu Rev Entomol. 2006;51(1):557-80. doi:10.1146/annurev.ento.51.1 10104.151150
94. Rechav Y, Whitehead GN. Field trials with pheromone-acaricide mixtures for control of Amblyomma hebraeum. J Econ Entomol. 1978;71(1):149-51. doi:10.1093/jee/71.1.149
95. Sonenshine DE, Haines G. A convenient method for controlling populations of the American dog tick, Dermacentor variabilis (Acari: Ixodidae), in the natural environment. J Med Entomol. 1985;22(5):577-83. doi:10.1093/jmedent/22.5.577
96. Sonenshine DE, Adams T, Allan SA, McLaughlin J, Webster FX. Chemical composition of some components of the arrestment pheromone of the black-legged tick, Ixodes scapularis (Acari: Ixodidae) and their use in tick control. J Med Entomol. 2003;40(6):849-59. doi:10.1603/0022-2585-40.6.849