Gonzaga *et al. Parasites & Vectors (2023) 16:415*
https://doi.org/10.1186/s13071-023-05969-w

Parasites & Vectors

REVIEW

Open Access

Essential oils and isolated compounds for tick control: advances beyond the laboratory

Bruno César Ferreira Gonzaga[1,2], Mayara Macêdo Barrozo[1], Ana Lúcia Coutinho[1], Lainny Jordana Martins Pereira e Sousa[1], Francisca Letícia Vale[1], Laís Marreto[3], Paula Marchesini[1], Daniel de Castro Rodrigues[4], Evandro Davanço Ferreira de Souza[5], Gustavo Adolfo Sabatini[6], Lívio Martins Costa-Júnior[7], Lorena Lopes Ferreira[8], Welber Daniel Zanetti Lopes[1,9] and Caio Monteiro[1,9*]

Abstract

Background Tick control is a worldwide challenge due to its resistance to acaricides. Essential oils (EOs) and isolated compounds (EOCs) are potential alternatives for tick control technologies.

Methods A review with EOs and EOCs, under field and semi-field conditions, was performed based on Scopus, Web of Science and PubMed databases. Thirty-one studies published between 1991 and 2022 were selected. The search was performed using the following keywords: "essential oil" combined with "tick," "*Ixodes*," "*Argas*," "*Rhipicephalus*," "*Amblyomma*," "*Hyalomma*," "*Dermacentor*," "*Haemaphysalis*" and "*Ornithodoros*." The words "essential oil" and "tick" were searched in the singular and plural.

Results The number of studies increased over the years. Brazil stands out with the largest number (51.6%) of publications. The most studied tick species were *Rhipicephalus microplus* (48.4%), *Ixodes scapularis* (19.4%), *Amblyomma americanum* and *R. sanguineus* sensu lato (9.7% each). Cattle (70%) and dogs (13%) were the main target animal species. Regarding the application of EOs/EOCs formulations, 74% of the studies were conducted with topical application (spray, pour-on, foam, drop) and 26% with environmental treatment (spray). Efficacy results are difficult to evaluate because of the lack of information on the methodology and standardization. The nanotechnology and combination with synthetic acaricides were reported as an alternative to enhance the efficacy of EOs/EOCs. No adverse reactions were observed in 86.6% of the studies evaluating EOs/EOCs clinical safety. Studies regarding toxicity in non-target species and residues are scarce.

Conclusions This article provides a comprehensive review on the use of EOs and EOCs to reduce tick infestations, in both the hosts and the environment. As future directions, we recommend the chemical characterization of EOs, methodology standardization, combination of EOs/EOCs with potential synergists, nanotechnology for new formulations and safety studies for target and non-target organisms, also considering the environmental friendliness.

Keywords Biopesticides, Botanicals, Eco-friendly, Field efficacy, Ixodidae, Tick control

*Correspondence:
Caio Monteiro
caiosat@gmail.com
Full list of author information is available at the end of the article

Background

In livestock animals such as cattle, ticks cause economic losses linked to lower body weight, live weight gain, milk production and leather quality. In addition, it leads to losses by the transmission of pathogens, mortality of cattle and costs associated with control [1, 2]. The lower productivity in herds directly impacts food production, thus representing a challenge based on the increase in world population, which is expected to reach the 9 billion mark by 2050 [3, 4].

In companion animals, ticks are responsible for blood spoliation and work as vectors of numerous pathogens (e.g. *Anaplasma platys*, *Babesia vogeli*, *B. canis, Ehrlichia canis* and *Hepatozoon canis*), impacting animal welfare and even causing death [5–7]. The increase in human population has led to a higher number of pets, as one third of families worldwide own a dog [8]. In addition, some families consider their animals as true family members because of their emotional bond [9]. Furthermore, ticks are also very important for public health, and cases of diseases generated by tick-borne pathogens in humans, such as anaplasmosis, ehrlichiosis, Lyme disease, spotted fever and tularemia, have increased considerably. Therefore, technologies to control these arthropods must be developed [10–12].

The control of ticks is mainly carried out with synthetic acaricides, composed of molecules belonging to the class of organophosphates, amidines, pyrethroids, phenylpyrazoles, macrocyclic lactones, growth inhibitors and isoxazolines [13, 14]. However, the continuous and irrational use of these drugs has resulted in tick populations resistant to almost all commercially available chemical classes. The occurrence of acaricide-resistant tick populations has been documented worldwide and for several tick species [15]. For example, there are already records of resistance for *Rhipicephalus microplus* [16–21], *R. sanguineus* s.l. [22–24], *R. annulatus* [25–29], *R. decoloratus* [30] and *Hyalomma anatolicum* [31].

In addition to the problem of tick resistance, the consumer market has increasingly demanded pest control technologies that are eco-friendly and aligned with the concepts of "One Health" and "Sustainability." Such aspects reinforce the development of new technologies to control these ectoparasites in a manner that is safe for humans, animals and the environment (One Health), in addition to being economically viable (Sustainability) [13, 32–34]. Essential oils (EOs) have shown potential for the development of ecofriendly acaricides [35]. These oils are natural products resulting from the secondary metabolism of aromatic plants, containing a mixture of about 20 to 60 volatile, fat-soluble and strongly odorous compounds [36]. In plants, EOs work by attracting pollinators and seed dispersers, repelling and combating parasites, pathogens and predators, in addition to assisting against abiotic stressors (Fig. 1) [35, 37, 38]. The compounds found in EOs (EOCs) can be divided mainly into two groups according to their biosynthesis: terpenes/terpenoids (such as monoterpenes and sesquiterpenes) and aromatic and aliphatic compounds, such as phenylpropanoids [36, 39].

The first studies regarding the use of EOs/EOCs for tick control [40–43] were published in the 1990s. Since then, several papers have been published demonstrating their acaricide and/or repellency activity [44–51], eventually demonstrating alterations in tick biological parameters and tissues [52–55]. Other studies provided details about the action mechanisms [56, 57] and formulation development using EOs or EOCs [58–60]. Finally, some review articles have been published on the subject [13, 61–66].

Although many studies have been produced, products on the market containing EOs or EOCs are still limited. This may be linked to the lack of studies on formulation development and efficacy evaluation under field conditions, as well as challenges related to the chemistry, manufacturing and control guidance. This review aimed to compile studies using EOs and EOCs (1991–2022) for tick control under field and semi-field conditions, presenting a critical analysis of the real state of the art of this research line, as well as suggesting priorities and directions for further studies. In addition, we present the point of view of the antiparasitic industry regarding the use of EOs and EOCs for tick control.

Search strategy

A literature review was carried out on articles published over the last 31 years (1991–2022) by searching in the following databases: Scopus, Web of Science and PubMed. The search considered the following keywords: "essential oil" combined with "tick," "*Ixodes*," "*Argas*," "*Rhipicephalus*," "*Amblyomma*," "*Hyalomma*," "*Dermacentor*," "*Haemaphysalis*" and "*Ornithodoros*." The terms "essential oil" and "tick" were searched in both the singular and plural (Fig. 2).

The inclusion criteria considered studies that used EOs or EOCs in field and semi-field studies for tick control. The exclusion criteria considered the following situations: articles reporting studies only under laboratory conditions, studies evaluating repellent activity, articles using plant extracts, duplicate articles, review articles, books, book chapters and meeting abstracts. In addition to the authors' expertise, a manual search process was performed by checking the list of references of the studies included in the review to identify and add eligible articles that were not retrieved by the initial search strategy. By the final search and application of the inclusion and

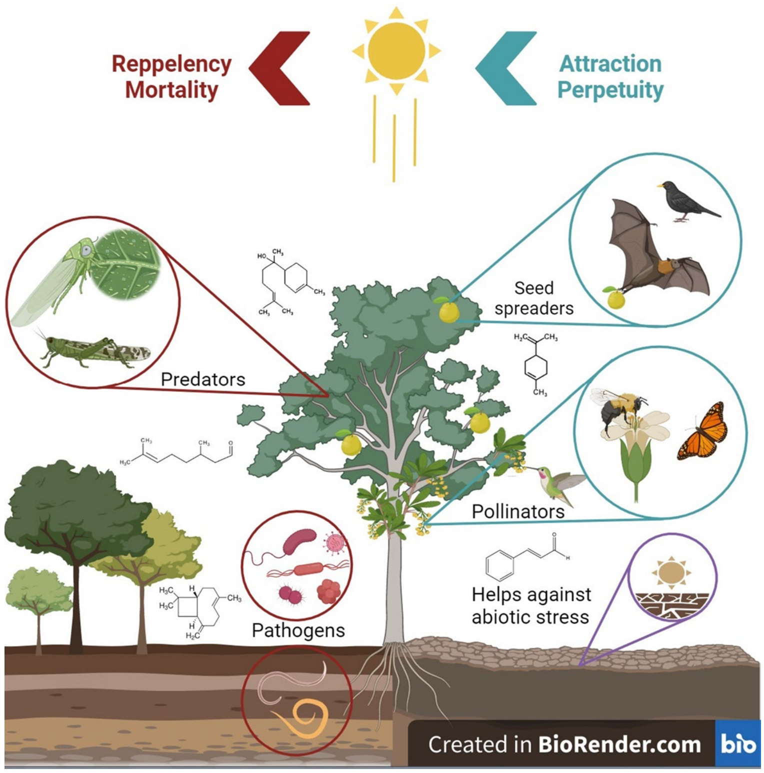

Fig. 1 Ecological interactions of plants mediated by essential oils. Circles in green represent the attraction of seed dispersers and pollinators. Red circles represent repellency and mortality of predators and pathogens. Circle in purple represents abiotic stress factors such as dry spells

exclusion criteria, 31 articles were selected for this review (Fig. 2).

Data from each article were compiled in a Microsoft Excel® spreadsheet, and the following parameters were evaluated: (1) year of publication; (2) country of the study; (3) type of trial; (4) number of animals; (5) host species; (6) tick species; (7) plant species used for extraction of the EOs/EOCs; (8) chemical characterization of the EOs; (9) concentration of the EOs/EOCs; (10) volume applied per animal or plot; (11) results of the acaricidal effect/efficacy on ticks; (12) clinical safety evaluation; (13) plot size; (14) evaluation in non-target organisms; (15) residue evaluation. A map showing the locations of the studies was produced using Microsoft Excel® software.

Research with EOs and EOCs for tick control under field and semi-field conditions

Publications per year

Thirty-one scientific articles were included in this review, with research using EOs from 19 plant species and studies using seven EOCs (Additional file 1: Figure S1, S2, S3, S4, S5 and S6). Between 1991 and 2000, only two articles (6.5%) were found, while for the following decade (2001 to 2010), six articles (19.4%) were featured. Most articles (15 publications, 48.4%) were published between 2011 and 2020, indicating a higher number of studies and greater interest in this research area. Notably, for the first 2 years of the current decade (2021–2022), eight publications were found, indicating this trend of increase in studies should remain over the next few years (Fig. 3). Such growth in the number of publications over the decades might be linked to multiple factors, including the increased number of acaricide-resistant tick populations and the need for new control technologies aligned with the concepts of One Health and Sustainability.

The number of publications worldwide has increased, thus addressing different species of ticks resistant to commercial acaricides [15], such as *Rhipicephalus microplus* [16–18, 21, 30, 67–75], *R. sanguineus* s.l. [22–24, 76–79], *R. annulatus* [59], *R. australis* [80], *H. anatolicum* [31], *R. appendiculatus*, *R. bursa*, *R. decoloratus*, *R. evertsi*, *Amblyomma mixtum* and *A. hebraeum* [81].

Publications by country

The research studies using EOs and EOCs in both field and semi-field conditions were conducted in eight countries, in the following order: Brazil (51.6%), the US (22.6%) and Egypt (9.7%) (Fig. 4). The greater representation of Brazil might be linked to multiple factors, including the particular severity of ticks regarding the livestock

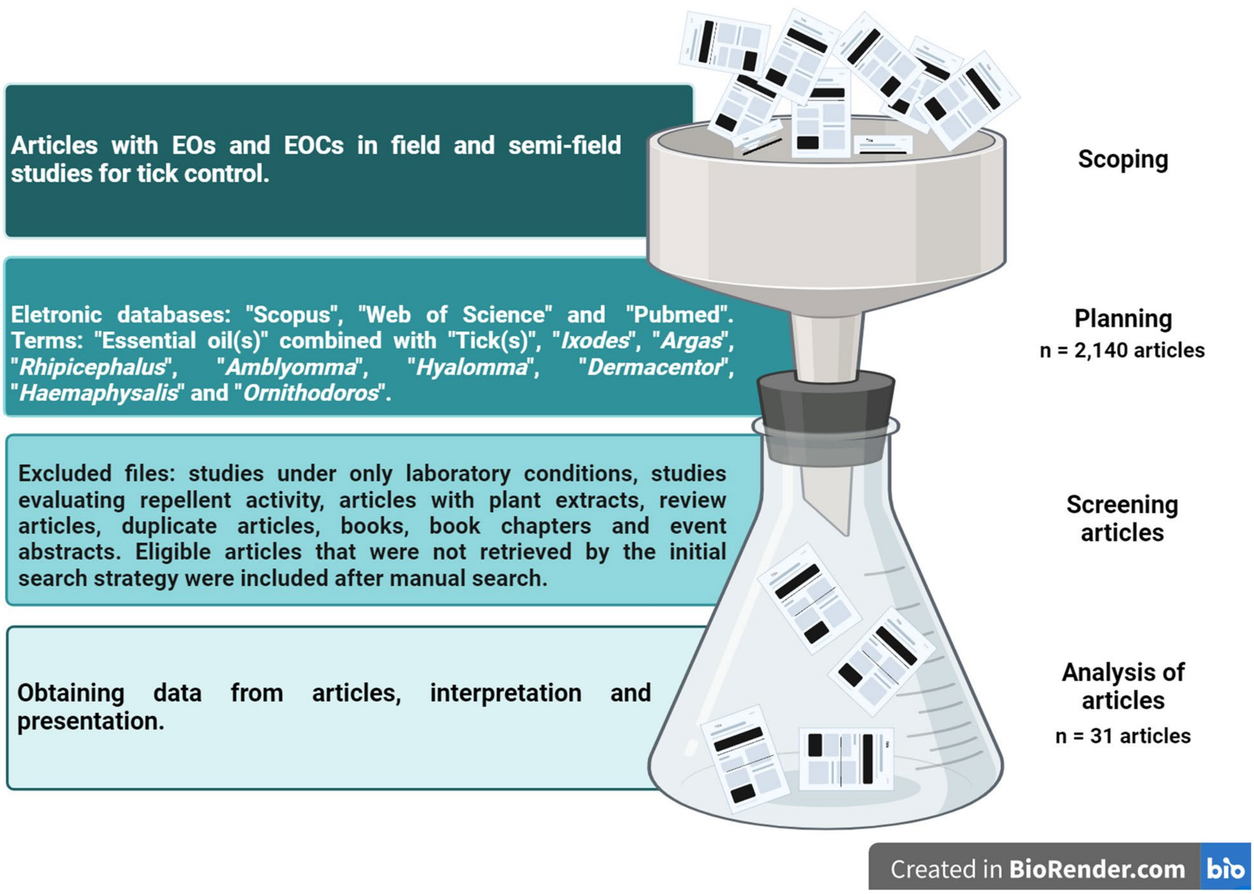

Fig. 2 Search methodology for studies with essential oils (EOs) and essential oil compounds (EOCs) for tick control under field and semi-field conditions ($n = 31$) published from 1991 to 2022

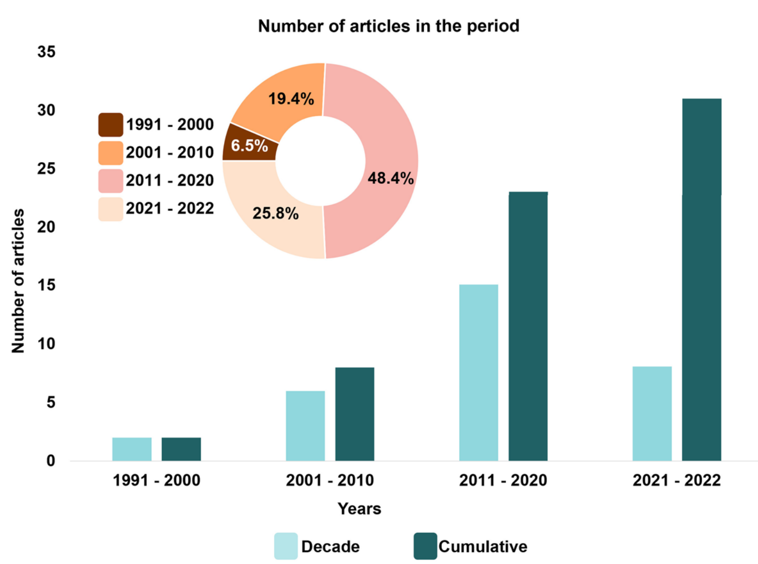

Fig. 3 Number of publications per decade (1991–2022) using essential oils (EOs) and essential oil compounds (EOCs) for tick control under field and semi-field conditions

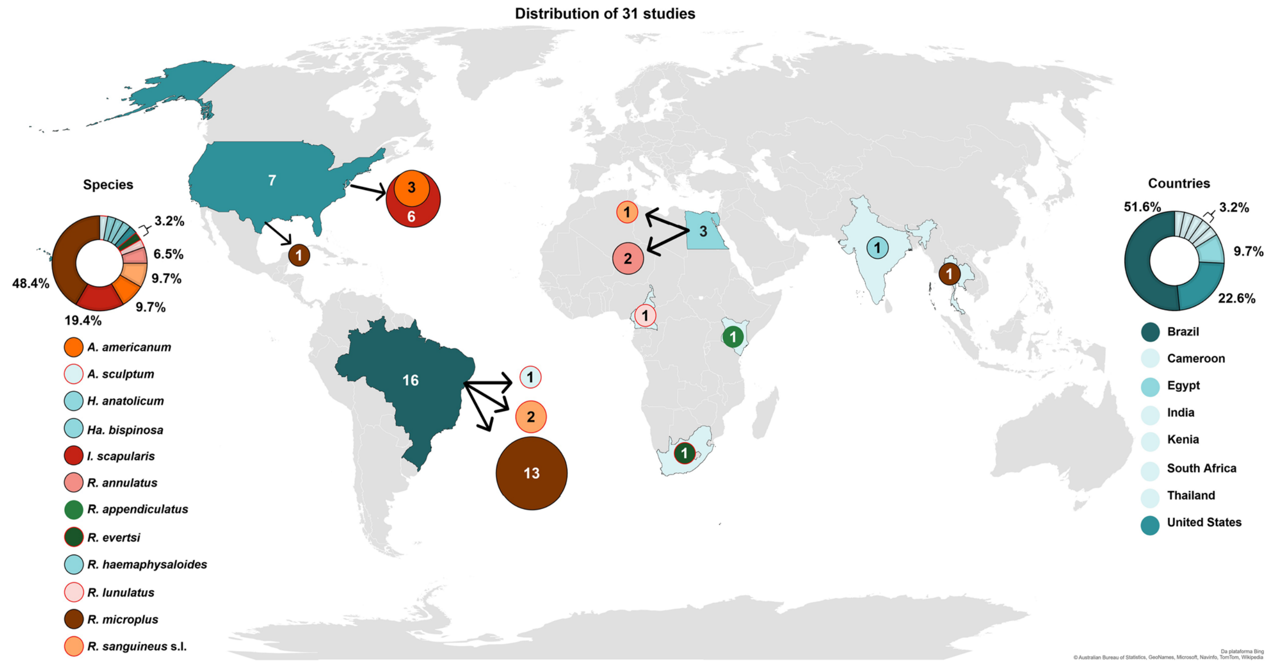

Fig. 4 Geographic distribution of 31 field and semi-field studies using essential oils (EOs) or essential oil compounds (EOCs) for tick control between 1991 and 2022. Colored circles, with sizes proportional to the number of studies, represent different species of ticks. Abbreviation of tick genera: *Amblyomma* (*A.*); *Ixodes* (*I.*); *Hyalomma* (*H.*); *Haemaphysalis* (*Ha.*); *Rhipicephalus* (*R.*). Source: adapted from the Bing platform, 2022

industry and animal health in the country, the huge plant diversity and culture of using natural products for health issues and the interest of some Brazilian researchers. Brazil has the largest commercial cattle herd in the world (224.6 million cattle) [82], being one of the biggest producers of beef (2.975 million tons per year) [83] and the fourth largest producer of milk [84] (35.3 billion liters per year) [82]. In addition, Brazil has the second largest dog population in the world (estimated at 58.1 million dogs) and takes in the sixth highest revenue in the global pet market [85, 86]. Therefore, there is a great demand for new technologies to control ticks on livestock and dogs in this country. Regarding plant biodiversity, Brazil has the largest number of described species in the world (55% of endemic terrestrial plant species) [87], hence the great biodiversity of raw material for studies on the activities of botanical compounds on ticks.

Publications by tick species

Rhipicephalus microplus (48.4%) was the most studied tick species, followed by *I. scapularis* (19.4%), *A. americanum* and *R. sanguineus* s.l. (9.7% each) and *R. annulatus* (6.5%). Research was also conducted with *Rhipicephalus lunulatus*, *R. evertsi*, *R. appendiculatus*, *Amblyomma sculptum*, *H. anatolicum*, *Haemaphysalis bispinosa* and *R. haemaphysaloides* (3.2% = one study with each species). All studies targeted ticks of economic or public health importance (Fig. 4, Tables 1, 2, 3).

Rhipicephalus microplus (cattle tick) was the most studied tick species, probably because of its wide geographic distribution and great economic importance for the cattle industry worldwide [88]. The annual losses attributed to this tick in Brazil and Mexico were estimated at \$3.24 billion and \$573.61 million, respectively [2, 89]. In addition, it is notable that most of the tick control products available on the market show low efficacy in controlling this tick [16, 71, 90] based on the increasing records of resistant populations, especially multidrug-resistant populations, in Central American, South American and Asian countries [15, 17, 18, 68–70, 73, 91, 92].

Ixodes scapularis (black-legged tick) was the second most studied species, followed by *A. americanum* (lone star tick) and *R. sanguineus* s.l. (brown dog tick). These first two species have great public health importance in the US as vectors of disease agents to humans [93]. The black-legged tick is the vector of the causative agents of diseases such as Lyme disease (*Borrelia burgdorferi*), human granulocytic anaplasmosis (*Anaplasma phagocytophilum*) and babesiosis (*Babesia microti*). The lone star tick is the vector of *Ehrlichia chaffeensis* (human monocytic ehrlichiosis) and *E. ewingii* (human granulocytic ehrlichiosis), *Borrelia lonestari* (tick-associated rash illness) and *Francisella tularensis* (tularemia) [12, 94, 95].

Table 1 General data (treatments and efficacy) compiled from 16 articles using essential oils (EOs) and essential oil compounds (EOCs) to control *Rhipicephalus microplus* and *R. annulatus* in cattle studies from 1991 to 2022

Tick (stage)	EOs/EOCs	Concentration	Volume and form of application	No. of animals/ treated group	Type of infestation	Main results	References
R. microplus (A)	*Cymbopogon citratus* and *C. nardus C. winteranius Jowitt* (major compounds: not mentioned)	…	… (Spray)	…	Field trial Natural	Semi-engorged females collected (after spraying) died 48 h after EO application and engorged females did not oviposit	Chungsamarnyart and Jiwaginda [183]
Rhipicephalus microplus (A)	*C. winteranius Jowitt* (major compounds: not mentioned)	10% and 100%	40 mL (pour-on); 2 L (spray)	15	Field trial Artificial	EO significantly reduced the number of ticks	Martins and González [124]
R. microplus (L, N, A)	*C. nardus* (major compounds: citronellal 50.07%, geraniol 13.87%, citronellol 7.93%)	4%	3 L each 7 days for 28 days (Backpack Sprayer)	5	Field trial Natural	Efficacy of 35.3%, 11.8%, 34% and 42.4% at days 7, 14, 21 and 28 after treatment	Agnolin et al. [157]
R. microplus (N, A)	*C. nardus* (major compounds: citronellal 50.07%, geraniol 13.87%, citronellol 7.93%)	3% and 4%	3 L, single treatment (Backpack sprayer)	5	Field trial Natural	Efficacy mean of 22.5 and 39.1% at concentrations of 3 and 4%, respectively, 28 days after treatment	Agnolin et al. [184]
R. microplus (L, N, A)	*Co. citriodora* (major compounds: citronellal 70.4%, isopulegol 16.3% and citronellol 5.5%)	3.5%	4 L (backpack sprayer)	6	Field trial Natural	Efficacy mean of 96.4%, 21 days after treatment	Olivo et al. [159]
R. microplus (L, N, A)	*Tagetes minuta* (rich in terpenes)	20%	50 mL (pour-on)	6	Pen trial Artificial	Efficacy of 99.98%	Andreotti et al. [140]
R. microplus (L, N, A)	*C. winterianus* (major compounds: not mentioned)	8.6%	4 L, single treatment (Backpack sprayer)	6	Field trial Natural	Efficacy mean of 90%, 21 days after treatment	Agnolin et al. [141]
R. microplus (L, N, A)	Original oil of *Co. citriodora* and modified oil of *Co. citriodora* (N-prop-2-inylcitronellylamine)	1.5% and 1.5%	… …	6	Field trial Natural	Treatment with EO (original and formulated) did not significantly reduce the number of ticks	Chagas et al. [185]
R. microplus (L, N, A)	*Melaleuca alternifolia* (major compounds: terpinen-4-ol 41.98%, γ-terpinene 20.15%)	0.75% (nano particle) and 5% (unformulated)	400 mL, single treatment (spray)	5	Field trial Natural	The unformulated EO had a greater effect on adults. Encapsulated nano EO had a greater effect on biology of ticks (34.5% efficacy)	Boito et al. [125]
R. microplus (L, N, A)	*Cinnamomum* sp. (major compound: cinnamaldehyde 41.27%)	0.5% (nanocapsules); 0.5% (nanoemulsion) and 5% (unformulated)	50 mL, single treatment (neck, legs, ventral and inguinal region)	4	Field trial Natural	Efficacy was 90.5%; 100% and 63.5% in treatments with unformulated EO, nanocapsules and nanoemulsion, respectively	Santos et al. [126]
R. microplus (L, N, A)	Eugenol	5%	10 mL/100 kg, single treatment (pour-on)	6	Pen trial Artificial	Efficacy mean of 13.80%, 20 days after treatment	Valente et al. [158]

Table 1 (continued)

Tick (stage)	EOs/EOCs	Concentration	Volume and form of application	No. of animals/treated group	Type of infestation	Main results	References
R. annulatus (L, N, A)	Thymol + deltamethrin Thymol + *E.globulus* + deltamethrin *E. globulus* (major compounds: not mentioned)	5%	… treated twice, 2-week interval (spray)	5	Field trial Natural	Efficacy mean of 88.33 and 95% for thymol + deltamethrin and thymol + *E. globulus* + deltamethrin. Engorged females deposited small egg masses unable to hatch	Arafa et al. [59]
R. microplus (L, N, A)	Essentria® IC-3 (rosemary oil 10%, geraniol 5% and peppermint oil 2%) EOs—major compounds: not mentioned	6.25%	7.5 L, single treatment (spray race)	4	Pen trial Artificial	Less engorged females recovered from the treated group for 21 days. Considering the biological parameters of ticks, the efficacy was 70%	Klafke et al. [142]
R. microplus (L, N, A)	(*E*)-cinnamaldehyde	0.1%	5 L, single treatment (backpack sprayer)	10	Field trial Natural	The animals showed signs of intoxication, such as sialorrhea and muscle tremors. The experiment was interrupted	Gonzaga et al. [21]
R. microplus (L, N, A)	*Lippia sidoides* (major compound: thymol 40.3%, p-cymene 17.2%, *E*-caryophyllene 8.99%)	1%	3 L, single treatment (backpack sprayer)	10	Field trial Natural	The efficacy range between day 3 to 28 after treatment was 23.3 to 63.2%	Pereira et al. [180]
R. annulatus (L, N, A)	*Pelargonium graveolens* (major compound: citronellol 14.44%, geraniol 11.08%, linalool 7.74%, citronellyl 7.66%)	10% nanoemulsion Combination with sesame oil	400 mL, single treatment (spray)	5	Field trial Natural	Efficacy mean of 87.97% and 74.83% for and *Pelargonium graveolens* nanoemulsion (nano) and *P. graveolens* + sesame oil. Females treated with *P. graveolens* (nano) did not oviposit	Ibrahium et al. [143]

Abbreviations of tick genera: *Rhipicephalus* (*R.*)

Abbreviations of the stages of ticks: larva (L); nymph (N); adult (A)

Abbreviations of the genera of plants: *Cymbopogon* (C.), *Corymbia (Co.), Tagetes (T.), Melaleuca (M.), Eucalyptus (E.), Lippia (L), Pelargonium (P.)*

…—Information not mentioned

Brown dog ticks have great importance in animal health as vectors of several pathogens for dogs, such as *E. canis*, *B. vogeli*, *Mycoplasma haemocanis* and *H. canis* [96]. In addition, *R. sanguineus* s.l. can also parasitize humans and act as vectors of *Rickettsia conorii* and *R. rickettsii*, among other disease agents [97–102]. Notably, resistance of *R. sanguineus* s.l. has also been described in pyrethroids, amidines, organophosphates, phenylpyrazoles and macrocyclic lactones [22–24, 78].

Despite also being of veterinary and public health concern, the other above-mentioned ticks are more geographically limited. For example, *R. annulatus* (North American Texas fever tick) is most prevalent in the Mediterranean region and has been eradicated from the US [103, 104]. The ticks *R. lunulatus*, *R. e. evertsi* (red-legged tick) and *R. appendiculatus* (brown ear tick) are found in Africa parasitizing livestock (horses, cattle, goats and sheep) and wildlife animals, such as African buffaloes and antelopes, causing morbidity and mortality in these animals [105]. In Brazil, *A. sculptum* is a tick that has capybaras, horses and tapirs as primary hosts but can accidentally feed on humans and transmit *R. rickettsii* [106]. Finally, *H. anatolicum*, *Ha. bispinosa* and *R. haemaphysaloides* are common in India (Asia) parasitizing small ruminants and horses [107].

Publications by compounds tested and chemical characterization of essential oils

Most field and semi-field studies used EOs (65%), followed by EOCs (19%) and both EOs and EOCs in 16% (Fig. 5a, Tables 1, 2, 3). The chemical composition was evaluated in 85% of the studies that used EOs; however, in some cases (20%), the characterization was not performed in the study itself but in a previous study conducted by the same research group. In 15% of these studies, chemical characterization of the EOs was not performed (Fig. 5b). Studies using commercial products containing EOs were not considered in this analysis.

It is known that the same plant species can present varied compositions and acaricidal activity according to the genotype, soil, collection site, time of year, harvest year, plant part used, extraction method and storage conditions [108–111]. It has been shown that EOs from the same plant species have differences in acaricidal activities due to variations in chemical composition [111–114]. Therefore, the chemical characterization of EOs is a fundamental aspect of identifying their active compounds.

There are advantages and disadvantages to using EOs and EOCs. As an advantage, EOs present lower toxicity to vertebrates compared to the major compounds isolated from them when tested alone [115]. Furthermore, their mixtures can result in synergistic effects due to the presence of compounds with different action mechanisms [35, 37]. As a negative aspect, EOs present variations in chemical composition, which can hinder commercial applications due to the lack of standardization, hence generating difficulties in quality control and obtaining raw materials on a large scale. A potential solution would be to work with marker compounds (putatively the active principles), including predetermined amounts of a key compound that can guarantee efficacy against ticks; however, it is not a simple task [116]. The EOCs have the advantage of standardization and the ease of obtaining the active ingredient on a large scale for developing commercial formulations. However, the use of compounds isolated from the EOs can raise the toxicity of the formulation for animals [115], as already demonstrated in guinea pig using (*E*)-cinnamaldehyde, a major compound found in cinnamon EO [21].

Experimental design: animal species, number of animals used and administration of the formulations on hosts and the environment

Variations occurred regarding the animal species, number of animals per treated group used in the experiments, volume of formulation applied to the animals and forms of application. Among the 31 field and semi-field studies using EOs and EOCs for tick control, 74% applied the formulations on the animals (cattle, dogs, goats, sheep and rabbits) (Fig. 5c and d, Tables 1 and 2), while 26% applied them in the environment (Fig. 5c, Table 3).

Species and number of animals used

Among the 23 studies using hosts, 70% (16/23) used cattle, 13% (3/23) dogs, 9% (2/23) goats, 4% (1/23) sheep and 4% (1/23) rabbits. The number of animals per treated group varied from 4 to 15 for cattle, 5 to 10 for dogs, 6 to 10 for goats, 1 for sheep and 9 for rabbits (Fig. 5d, Tables 1 and 2).

In this regard, the first version of the guidelines of the World Association for the Advancement of Veterinary (WAAVP) for evaluating the efficacy of acaricides against ticks of ruminants recommended a minimum of three animals per group [117]. The new guidelines, published in 2022, recommended a minimum of 20 animals per treated group [118]. These recommendations may vary regionally. As an example, Brazilian legislation recommends the use of 10 animals per group [119]. For dogs, the WAAVP recommends a minimum of six animals per group [120, 121].

Animal experimentation with a larger number of animals poses a challenge for conducting research under field and semi-field conditions due to cost and ethical issues. Thus, there must be efforts to find alternatives to such a challenge by respecting the principles of the 3Rs (replacement, reduction and refinement) of

Table 2 General data (treatments and efficacy) compiled from seven articles using essential oils (EOs) and essential oil compounds (EOCs) for tick control in studies with dogs, rabbits, sheep and goats from 1991 to 2022

Tick (stage)	Host	EOs/EOCs	Concentration	Volume and form of application	No. of animals/treated group	Type of infestation	Main results	References
Rhipicephalus appendiculatus (L, N, A)	Rabbits	*Ocimum suave* (major compound: not mentioned)	2, 5 and 10%	5 mL per ear (topical spray)	9	Artificial	Mortality of 100 for larvae and nymphs and 74.5% for adults at a concentration of 10%	Mwangi et al. [135]
Hyalomma anatolicum; *Haemaphysalis bispinosa*; *Rhipicephalus haemaphysaloides* (–- – "tick count")	Goats	*Cymbopogon citratus* and *C. nardus* (major compound: not mentioned)	25, 33 and 50%	…, single treatment (spray)	6	Natural	Lemongrass oil eliminated all ticks in 24 h and citronella oil in 48 h	John et al. [132]
Rhipicephalus evertsi (N, A)	Sheep	*Th. trilobata* (major compound: alpha-pinene 21.6%, alpha-phellendrene 21%, limonene 12.8%)	5 mg/mL and 10 mg/mL	2 drops in the attachment site of the tick (ear, genital/anal areas)	1	Natural	Mortality of 100% (n = 7) of ticks at a concentration of 10 mg/mL	Peebles et al. [134]
Rhipicephalus lunulatus (L, N, A)	Goats	*Ch. ambrosioides* (major compound: not mentioned)	0.06, 0.09 and 0.12 µL/g	Soap (foam) twice a day, focusing on points where ticks are	10	Natural	Mortality (cumulative) after the 8th day was 76.12, 90.27 and 96.29%, at concentrations of 0.06, 0.09 and 0.12 µL/g, respectively	Kouam et al. [133]
R. sanguineus sensu lato (L, N, A)	Dogs	*T. minuta* (major compound: not mentioned)	20%	20 µL (topical spray)	5	Artificial	The EO resulted in 100% efficacy, the ticks died 24 h after application	Silva et al. [130]
R. sanguineus sensu lato (A)	Dogs	Lacecca® (Allicin + *A. sativum* + *B. napus*)	0.05 + 2.5 + 8%	0.25 mL/kg for 3 days (oral spray)	10	Artificial	EO resulted in 100% efficacy in preventing infestation by *R. sanguineus* s.l. and a treatment efficacy of 75 to 99% from the first to the third dose	Amer and Amer [131]
R. sanguineus sensu lato (L, N, A)	Dogs	Thymol + eugenol	5 + 5 mg/mL (0.50% (p/p)	10 mL/kg (topical spray)	5	Artificial	The nanoemulsion reduced the number of larvae on the animals and affected the reproductive parameters of engorged females (percent control = 85%)	Monteiro et al. [60]

Abbreviations of tick genera: *Rhipicephalus* (*R.*); *Hyalomma* (*H.*); *Haemaphysalis* (*Ha.*)

Abbreviations of the stages of ticks: larva (L); nymph (N); adult (A)

Abbreviations of the genera of plants: *Cymbopogon* (C.), *Ocimum (O.), Thelechitonia (Th.), Tagetes (T.), Chenopodium (Ch.), Allium (A.), Brassica (B.)*

…—Information not mentioned

Table 3 Treatment and efficacy compiled from eight articles using essential oils (EOs) and their compounds (EOCs) for tick control in environmental studies from 1991 to 2022

Tick (stage)	EOs/EOCs	Type of infestation	Concentration	Plot size	Main results	Reference
I. scapularis and *A. americanum* (N, A)	Nootkatone; Nootkatone nanoemulsion and Carvacrol	Naturally infested environment	1; 2; 5%; 3.1% (nanoemulsion) and 0.05; 5%	100 m^2	Two compounds (5%) were able to suppress 100% the nymphs of *I. scapularis* and *A. americanum* for 2 days, maintaining an efficacy > 65% up to 21 days after application	Dolan et al. [150]
I. scapularis (L, N, A)	Eco-Exempt IC2 (10% rosemary oil, 5% geraniol, 2% peppermint oil)	Naturally infested environment	3.1%	10,000 m^2 (L, N) and 100 m^2 (A)	Efficacy of 100%, 2 weeks after application. In larvae, the control was 63.1% (5 weeks post spray). For adults, the control was 93.8% in the 14th week post spray	Rand et al. [186]
I. scapularis and *A. americanum* (N)	Nootkatone	Naturally infested environment	2%	100 m^2	Efficacy of 96.5% for *I. scapularis* and 91.9% for *A. americanum,* after 42 and 35 days, respectively	Jordan et al. [146]
	Eco Trol T&O (10% rosemary oil, 2% peppermint oil and 0.5% sodium lauryl sulfate, with wintergreen oil, vanillin, lecithin and butyl lactate)		46.9 mL/L and 78.1 mL/L	100 m^2	The applications resulted in 90.8 and 87.3% control of *I. scapularis* and *A. americanum*, respectively	
	Carvacrol		2%	100 m^2	The applications resulted in 92.3% and 92.9% control of *I. scapularis* and *A. americanum*, respectively	
Ixodes scapularis Say (N)	Nootkatone	Naturally infested environment	0.46–0.84%	150–387 m^2	Efficacy of 100% for *I. scapularis* nymphs after 3 days and 49% after 16 days. With lignin encapsulation, the efficacy was 100% throughout during 56 days	Bharadwaj et al. [147]
Ixodes scapularis Say (L, N, A)	Eco-Exempt IC2 (10% rosemary oil, 5% geraniol, 2% peppermint oil)	Naturally infested environment	3.1%	100 m^2	IC-2 was as effective as bifenthrin (pesticide) in L, N and A and was less toxic in non-target species	Elias et al. [167]
R. microplus (L)	Crystals of thymol	Experimentally infested environment	2.5; 5; 10; 15 and 20 mg/mL	0.05 m^2	At the highest concentrations (10, 15 and 20 mg/mL) the number of live larvae decreased by > 95% compared to the control group	Araújo et al. [148]

Table 3 (continued)

Tick (stage)	EOs/EOCs	Type of infestation	Concentration	Plot size	Main results	Reference
A. sculptum (L)	Thymol + eugenol and carvacrol + eugenol	Experimentally infested environment	5 mg/mL	0.03 m^2	Efficacy in treatments with thymol + eugenol and carvacrol + eugenol was 63 and 42%, respectively	Vale et al. [152]
I. scapularis and *A. americanum* (N, A)	Essentria® IC-3 (10% rosemary oil, 5% geraniol, 2% peppermint oil)	Naturally infested environment	86.6 mL active ingredient/plot	100 m^2	First application (April)—Efficacy exceeding 90% for 3 weeks for nymphs; second application (May)—efficacy of 100% and ≥ 90% for *I. scapularis* and *A. americanum* nymphs for another 3 and 2 weeks, respectively. For adults, efficacy was low	Schulze and Jordan [149]

Abbreviations of tick genera: *Ixodes* (*I.*), *Amblyomma* (*A.*); *Rhipicephalus* (*R.*)

Abbreviations of the stages of ticks: larva (L); nymph (N); adult (A) animal research [122]. In this sense, it is also important to develop tests in animal models, predictive tests, computational modeling and validation alternatives for formulations developed with EOs and EOCs [123].

Formulations and administration on hosts

The formulations and administration routes of EOs/EOCs most used on hosts, topical spray (81%) was the most frequent, followed by pour-on (10%), drop on the tick attachment site (3%), soap foam (3%) and oral spray (3%). One publication did not describe the administration route (Fig. 5e, Tables 1 and 2).

In the publications with cattle using spray formulations, in 53% of the studies, at least three liters of solution was applied per animal (Table 1). As to the volume of formulation, Martins and González [124] used 2 L of solution in experimentally infested cattle weighing 350 kg, while Boito et al. [125] and Santos et al. [126] used only 400 mL and 50 mL, respectively, in naturally infested adult cattle. However, Santos et al. [126] performed the application only on the neck, legs, and inguinal and ventral regions of these bovines. Some of the studies did not report the formulation or volume applied, the age category (young, adult) or the weight of the animals. For spray commercial acaricides, it is recommended to treat the whole body of the bovine using 4–5 L (1 L per 100 kg animal), whereas, for pour-on formulations, the dosage varies according to the animal body weight and the dorsal line of the animal is treated [16, 127–129].

For dogs, two studies used a topical non-commercial formulation [60, 130] and one used an oral commercial formulation [131]. All works used experimental tick infestations (Table 2). Silva et al. [130] released the ticks in a chamber (5 × 3 cm) glued on the back of the dogs. The area of the chamber was sprayed once with 20 µL wild marigold (*Tagetes minuta*) EO after 24 h of tick infestation. Monteiro et al. [60] released the ticks on the dog's nape and the dogs were secured for 10 min to allow tick distribution. After 24 h, the whole body of the dogs was sprayed once with thymol + eugenol EOCs microemulsion (10 mL/kg). In turn, Amer and Amer [131] sedated the animals and released the ticks on the dogs' fur of the back, lateral side and head. The dogs received the spray oral treatment with Lacecca® (garlic oil 2.5%, allicin 0.05%, rapeseed oil 8%) for 3 successive days/month, before or after the tick infestation, depending on the group, at the dosage of 0.25 mL/kg.

For small ruminants (Table 2), soap foams of mastruz (*Chenopodium ambrosioides*) EO and spray lemongrass EO (*Cymbopogon citratus* and *C. nardus*) were used on naturally infested goats against different tick species [132, 133]. Three concentrations of soap with *C. ambrosioides* EO were developed, and the soap foam was applied on the goats, twice a day (morning and evening), focusing on points where *R. lunulatus* were present [133]. In turn, drops of wedelia (*Thelechitonia trilobata*) EO were applied on *R. e. evertsi* attachment sites in naturally infested sheep [134]. In addition to their differences in administration, it is impractical to use foam and drops at the site of tick attachment as a management routine on extensive farming of small ruminants as, once attached, ticks that parasitized goats and sheep, such as *R. e. evertsii* and *R. lunulatus*, prefer to feed mainly inside ears and tail (near genital/anal region). The work developed in rabbits (New Zealand) held in cages was developed with an experimental infestation on the rabbit ears using a cotton bag [135]. The alfavaca (*Ocimum suave*) EO was sprayed 5 mL per ear on the 2nd day of *R. appendiculatus* feeding using a laboratory animal, which is not with the preferred host. In addition, there are no studies in the same scenario for comparison and discussion.

Administration of the formulations in the environment

Eight studies using EOs/EOCs for tick control in the environment (field or semi-field conditions) were evaluated (Table 3). The studies were performed in either naturally or experimentally infested areas covering different plot sizes using spray formulations. The targeted ticks were those of public health importance (*I. scapularis*, *A. americanum* and *A. sculptum*), whose main hosts are usually wild animals. Managing wild animals is known to be difficult, thus requiring adopting different measures, such as applying acaricides in the environment.

For example, in endemic and risk areas for spotted fever rickettsiosis in Brazil, *A. sculptum* populations are usually maintained by capybaras (*Hydrochoerus hydrochaeris*). The application of acaricides on capybaras may not be an easy task and the fact that the animals constantly enter the water may represent an environmental issue [136–138]. Similar issues occur in the US for the control of *I. scapularis*, where the tick populations are maintained by wild animals, such as *Peromyscus leucopus* (white-footed mouse), other rodents and birds [95]. However, the use of topical or oral acaricides is now a reality in the US to control *I. scapularis* and *A. americanum* ticks on *Odocoileus virginianus*, the white-tailed deer [139].

Efficacy and alternatives to increase the efficacy of EOs/EOCs

Efficacy of EOs/EOCs for on-host tick control

Regarding the efficacy of trials using hosts, a worrisome aspect in the review of the selected articles was the lack of information about how the tick counts were performed, the stages of ticks counted and the calculations of efficacy or mortality. Thus, we found different efficacy

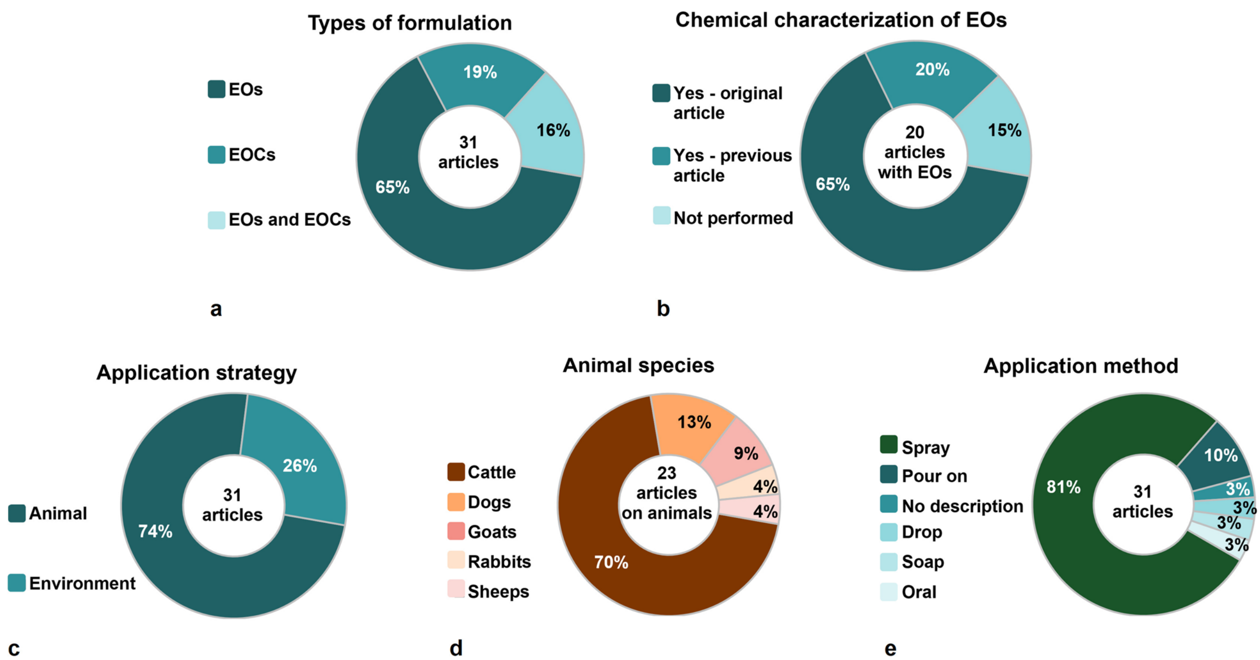

Fig. 5 Field and semi-field studies (*n* = 31) using essential oils (EOs) and essential oil compounds (EOCs) for tick control in the period 1991–2022. **a** Percentage of studies with EOs and EOCs. **b** Percentage of studies that performed chemical characterization of EOs or not; **c** percentage of EOs and EOCs application strategies; **d** percentage of animal species used in studies with EOs/EOCs; **e** percentage of methods for applying EOs/EOCs to animals and the environment

values without standardization of the articles, thus hampering comparison (Tables 1, 2). Such a scenario highlights that studies using EOs/EOCs have not typically followed international guidelines for evaluating the efficacy of acaricides, hence lacking standardization.

The most recent antiparasitic guidelines for acaricide registration require studies in pen facilities or fields, using both treated and control groups (untreated), with a preferred efficacy ≥ 90% [118]. Andreotti et al. [140] and Agnolin et al. [141] have reported results indicating an efficacy ≥ 90% in studies with cattle involving experiments that followed aspects mentioned in the most current guidelines [118] for efficacy verification (Table 1). The first study tested a pour-on formulation based on *T. minuta* EO at 20% on experimentally infested cattle (pen study) and obtained an efficacy of ≈100% after 13 days post-treatment (DPT). The second study performed a trial in naturally infested cattle with systematics tick counts (field study). The formulation of *Cymbopogon winterianus* EO at 8.6% was applied on cattle using a backpack sprayer. After 21 DPT, the efficacy was ≈90%. In contrast, Klafke et al. [142] tested a commercial spray with rosemary oil 10% (EO), geraniol 5% (EOC) and peppermint oil 2% (EO) (Essentria® IC-3, 6.5%) on experimentally infested cattle and observed an efficacy of 70%, 21 DPT.

Some works evaluated the treatment efficacy of EOs and EOCs in ticks infesting cattle differently than the guidelines [118], without an untreated control group. In these studies, the number of ticks was counted before and after treatment. In addition, some studies evaluated efficacy by analyzing the biology of recovered females after treating the cattle. These studies evaluated the biological parameters of engorged females in the laboratory to reach an efficacy value according to tick weight, egg mass weight and hatchability larval. Among the studies selected, Santos et al. [126], Arafa et al. [59] and Ibrahium et al. [143] accessed efficacy and found results > 70% and significantly lower tick counts after treatment (Table 1).

Santos et al. [126] used a cinnamon EO in three forms: pure oil (5%), nanocapsules (0.5%) and nanoemulsion (0.5%). Four cows from each group were sprayed with 50 mL of the tested formulation, and the test was performed on naturally infested cattle (Table 1). Animals sprayed with pure and nanoencapsulated cinnamon oil had significantly fewer ticks on days 1 and 4 post-treatment and were free of ticks on day 20 post-treatment. Engorged females collected 24 h after treatment had impaired oviposition and larval hatching, with treatment efficacy of 90, 100 and 63% to pure oil, nanocapsules and nanoemulsion, respectively.

Arafa et al. [59] tested deltamethrin, deltamethrin + thymol (EOC) and deltamethrin + thymol

(EOC) + eucalyptus 5% (EO) against *R. annulatus*. Naturally infested cows from each group were sprayed with the tested formulation, and the efficacy on day 30 post-treatment was 21.6, 88.3 and 95%, respectively (Table 1). Ibrahium et al. [143] evaluated the acaricidal activity of mallow (*Pelargonium graveolens*) EO 10%. Five naturally infested cattle were sprayed with 400 mL nanoemulsion of *P. graveolens* or *P. graveolens* + sesame oil. The authors observed that both treatments reduced the tick burden by 88% and 75%, respectively, 21 DPT. From females collected 72 h after treatment, only those treated with the nanoemulsion laid no eggs.

Here, it is worth discussing the relationship between the EOs/EOCs concentrations and efficacy. Changing the dose or the concentration of the active ingredient of an acaricide formulation is a known strategy to circumvent the resistance mechanisms of ticks [91]. However, regarding EOs and EOCs, increasing the concentration can impact the feasibility of formulations due to the high cost linked to the volume (4 to 5 L) required to spray a bovine completely. Increasing concentration, coupled with applying a volume of 4 to 5 L, can also increase the chance of cattle intoxication [21]. For small ruminants, the studies used different routes of administration, making results difficult to compare (Table 2).

In studies using five experimentally infested dogs (Table 2), 100% efficacy was reported against all stages of *R. sanguineus* s.l. evaluated 24 h after spraying *T. minuta* EO at 20% [130]. The use of a commercial product containing a mixture of garlic (2.5%), allicin (0.05%) and rapeseed (8%) EOs resulted in a treatment efficacy of 75–99% from the first to the third oral dose and a preventive efficacy of 100% against experimental infestation of *R. sanguineus* s.l. in 10 dogs [131]. Monteiro et al. [60] used a nanoemulsion containing thymol and eugenol EOC (5 mg/mL) sprayed on five experimentally infested dogs and observed a lower number of larvae, but not nymphs and adults, 3 DPT. However, there was an 85% reduction in the offspring (eggs and larvae) of engorged female *R. sanguineus* s.l. recovered from the treated dogs. In addition, the engorged larvae and nymphs recovered from the treated groups did not molt. Differently from cattle, the volume of application per dog is much lower, increasing economic viability and allowing the use of higher product concentrations for the treatment of these animals.

Overall, experimental studies have indicated that immature ticks (larvae and nymphs) are more susceptible to EOs and EOCs than adults (Table 2) [60, 135]. This could be related to the features of the cuticle in immature and adult tick stages [144, 145], although this has not been properly assessed. The studies with goats and sheep cannot be considered for discussion because of the lack of information.

Efficacy of EOs/EOCs for tick control in the environment

Table 3 shows the details of the studies using EOs/EOCs in the environment, such as tick stages, active compounds, concentration, plot size and efficacy. The efficacy exceeded 90% in half of the studies evaluated [146–149]. However, in some studies efficacy dropped over the evaluation period, requiring new applications to maintain tick suppression in the studied areas [146, 147, 149, 150]. The low persistence and consequently decreased control rate of EOs/EOCs may be linked to their high volatility [36, 61], which can be corrected by using encapsulated formulations [151]. For instance, Dolan et al. [150] observed that using a formulation with the concentration of 2% nootkatone EOC, applied by a high-pressure sprayer, was as effective as a formulation containing 5%, applied by a backpack pump. These authors also noted that a formulation using nanotechnology increased the effectiveness of nootkatone EOC. Improvements in the formulation process, such as the nanoemulsion used by Dolan et al. [150] and the encapsulation in lignin used by Bharadwaj et al. [147], allowed the use of lower concentrations and increased the efficacy period of the product against *I. scapularis* and *A. americanum*.

In addition, combinations between EOs and EOCs can maximize efficacy, as demonstrated by Vale et al. [152]. Under laboratory conditions, these researchers found that binary combinations of thymol, carvacrol and eugenol EOCs showed synergistic effects against *A. sculptum*, allowing increased efficacy with the use of lower concentrations, in addition to reducing the costs. In the field, they observed that the combination of thymol (5.0 mg/mL) + eugenol (5.0 mg/mL) EOCs resulted in 63% efficacy, while the combination of carvacrol (5.0 mg/mL) + eugenol (5.0 mg/mL) EOCs presented 42% efficacy.

Alternatives to increase the efficacy of EOs and EOCs

Nanotechnology

Six of the reviewed articles used nanotechnology to create formulations with EOs/EOCs (Tables 1, 2, 3). Using nanotechnology for formulation development is known to increase efficacy results and allow the use of lower concentrations of EOs and EOCs, which also increases the economic feasibility of the development of these biopesticides [65].

For example, against *R. microplus*, three studies demonstrated differences in the treatment efficacy when using nanotechnology (Table 1). By using tea tree (*Melaleuca alternifolia*) oil in nanocapsules (0.75%) and in its pure form (5%), Boito et al. [125] observed a control reduction of 34.5 and 0%, respectively, on tick reproductive biology, evidencing that nanoencapsulation increased efficacy. Santos et al. [126] found similar results using *Cinnamomum* sp. EO nanoencapsulated (0.5%), in nanoemulsion (0.5%) and its pure form (5%), with control reductions on *R. microplus* reproductive biology of 100%, 63.5% and 90.5%, respectively. Ibrahium et al. [143] verified that the nanoemulsion of *P. graveolens* EO was better than the association of *P. graveolens* EO with sesame oil. Only the females treated with the nanoemulsion did not oviposit. Against *R. sanguineus* s.l., Monteiro et al. [60] used nanoemulsion with thymol and eugenol (5 + 5 mg/mL = 1% active) EOCs on dogs, with larval reduction and 85% efficacy on the reproductive biology of engorged females (Table 2).

Dolan et al. [156] applied nootkatone EOC in the environment (shrub and litter layer) to suppress *A. americanum* and *I. scapularis* nymphs and observed a higher reduction of the ticks with the use of a nanoemulsion compared with a simple emulsion, 28 DPT (Table 3). Bharadwaj et al. [153] observed that a formulation of lignin-encapsulated nootkatone, applied in a residential lawn perimeter, resulted in 100% of control for *I. scapularis* nymphs for 56 days, whereas an emulsifiable formulation of nootkatone showed 100% control of the nymphs for only 7 days.

EOs/EOCs combined with synthetic acaricides

The association of EOs/EOCs with synthetic acaricides is another possibility to improve efficacy (Table 1), with an approach to find a synergistic effect as demonstrated in laboratory assays using eucalyptus EO + thymol EOC + deltamethrin against *R. annulatus*, and thymol EOC + cypermethrin, (*E*)-cinnamaldehyde EOC + amitraz and (*E*)-cinnamaldehyde EOC + chlorfenvinphos against *R. microplus* [21, 57, 59]. The Brazilian market already has formulations of commercial acaricides containing pyrethroids and organophosphates associated with terpenes (citronellal and geraniol EOCs) or piperonyl butoxide [153], a semisynthetic derivative of safrole EO, which is a phenylpropanoid found in plants of the genus *Piper* [154].

Initial data with *R. microplus* indicate that there is no cross-resistance between synthetic acaricides and EOs/EOCs [92, 155, 156]. In other words, tick populations resistant to commercial acaricides are not resistant to EOs/EOCs. Thus, combinations of synthetic acaricides with EOs/EOCs are an interesting alternative to be further investigated [92, 155, 156].

Two field studies in this review associated EOs/EOCs with synthetic acaricides (Table 1) [21, 59]. Arafa et al. [59] used a combination of eucalyptus EO + thymol EOC + deltamethrin that resulted in 95% efficacy in controlling *R. annulatus* infestations in cattle; in turn, when using only deltamethrin, the effectiveness was 21%. Gonzaga et al. [21] evaluated a combination of (*E*)-cinnamaldehyde EOC + amitraz against *R. microplus* in cattle. However, a few minutes after treatment the bovines showed intoxication signs, and the experiment could not proceed.

Clinical safety for hosts

Of the 23 articles using EOs/EOCs applied on animals, 65.2% evaluated at least one variable regarding the safety of the formulations for animals, such as heart and respiratory rates, rectal and eyeball temperatures, dehydration and mucous membrane coloration changes. Among these variables, no adverse changes were reported in 86.6% of the studies. However, few studies have performed more complete evaluations, including on hemogram, biochemical, clinical and dermal changes (Table 4).

For cattle, three studies verified the hemogram. Hemogram was performed in a study using *C. nardus* EO at 4% [157], while biochemical evaluation was also performed in studies including *C. winteranius* EO pure and at 10% [124] and eucalyptus (*Eucalyptus globulus*) EO at 5% + thymol EOC + deltamethrin [59] (Tables 1 and 4). The clinical evaluation did not describe the clinical parameters evaluated in the studies using cattle by Valente et al. [158], Arafa et al. [59] and Klafke et al. [142]. Heart and respiratory rate values and eyeball temperature were evaluated in the studies with Holstein cattle by Olivo et al. [159] and Agnolin et al. [141]. An adverse reaction was perceived only in the study of Gonzaga et al. [21], in which the Simmental cattle treated with (*E*)-cinnamaldehyde EOC at 0.1% showed sialorrhea and muscle tremors. Arafa et al. [59] observed a dermal alteration in a bovine sprayed with 1 mL/L of thymol EOC, with precipitation of thymol crystals appearing on the animal's skin, causing local irritation. Dermal evaluation, in cases of toxicity, may reveal allergic dermatitis and urticarial lesions in addition to reddening and warmth of the skin as a function of vasodilation caused by rubefacient agents, as observed for some EOs [160, 161].

For dogs, hemogram and biochemical analyses were performed before and after the treatment using a commercial product based on allicin and EOs of garlic (*Allium sativum*) and rapeseed (*Brassica napus*) [131] in addition to a formulation containing a combination of thymol with eugenol EOCs [60] (Tables 2 and 4). There was no change in the blood count and biochemistry parameters of treated dogs in these studies. Monteiro et al. [60] evaluated the rectal temperature, hydration, heart and respiratory rates as well as mucous membrane coloration and general physical condition of English Cocker Spaniel dogs treated with a nanoemulsion containing thymol (5.0 mg/mL) + eugenol (5.0 mg/

mL) EOCs. No dermal alterations were observed, a fact that may be related to the stability presented by the formulation, preventing the precipitation of thymol EOC. Another factor that might explain the absence of dermal reactions is the presence of eugenol EOC in the formulation. Data have shown that the presence of eugenol EOC minimizes or even prevents skin reactions caused by other compounds also present in EOs [115, 162].

For small ruminants, clinical signs and clinical pathological abnormalities have not been evaluated (Tables 2 and 4). Kouam et al. [133] only reported that goats treated with the *C. ambrosioides* EO soap foam did not change their behavior. However, the authors did not present details regarding this evaluation.

It is important that future studies properly assess the safety of EOs and EOCs in addition to the evaluation of efficacy. A standardized evaluation of clinical signs and clinicopathological abnormalities would allow a proper comparison of different treatment regimens in addition to providing more accurate data regarding EOs and EOCs safety.

Non-target organisms: residues and toxicity

The EOs possess numerous biological activities and are effective against various pests, having little or no toxicity against non-target species, as demonstrated in the EOs of species like fennel (*Foeniculum vulgare*), stevia (*Stevia rebaudiana*) and cinnamon (*Cinnamomum cassia*) [163–166]. In this review, toxicity effects on non-target species or description of residues in the environment were evaluated in only 25% of field and semi-field studies conducted in the environment (Table 3) [147, 167]. There were reports of decreased numbers of non-target arthropods of the orders Coleoptera, Hymenoptera and Collembola 1 week after the application of a product based on rosemary and peppermint EOs + geraniol EOC [167]. Phytotoxicity of products based on rosemary and peppermint EOs + geraniol EOC and emulsifiable nootkatone EOC was also reported. However, the authors mention that this phytotoxicity was reversed days after application [147, 167].

These assessments are important, especially in studies in the environment, as there is evidence of toxicity of EOs from bushy mat grass (*Lippia alba*), *L. gracilis*, spiced rosemary (*L. sidoides*), wild mint (*Mentha arvensis*), peppermint (*M. piperita*), clove basil (*Ocimum gratissimum*), pepper plants (*Piper aduncum* and *P. callosum*) and the hydrolate of common wormwood (*Artemisia absinthium*—a byproduct of its EO) on micro-crustaceans, plant seeds, algae and nematodes [168–170]. One possibility to decrease and even avoid phytotoxicity is encapsulation with lignin, as used by Bharadwaj et al. [147]. These alternatives such as the use of nanotechnology can reduce potential risks to animals and non-target organisms [171].

Animal health industry point of view

The industry plays a fundamental role in the development of new acaricides, of either chemical origin or not, by translating research into tangible products. The global animal health sector was valued in 2021 at $38.3 billion, and the parasiticide sales corresponded to the biggest chunk of the market, accounting for 34.1% of the revenues, followed by vaccines (28.5%), other products (22.2%) and antimicrobials (15.2%) [172]. In Brazil, the animal health sector moved approximately $2 billion, with parasiticides representing about 25% of the revenues [153]. Overall, this highlights the importance of parasites for the animal health sector globally.

The commercial attractiveness of the parasiticide segment attracts significant investment for the development of new solutions for parasite control annually [173]. However, sales potential is not the only motivating factor for a new project; additional financial indicators, like expected profitability and net present value (NPV), also play an important role in the decision process. Other aspects to be considered before starting a project for the development of a new antiparasitic are the strategic fit with the overall company strategy, technical feasibility and legal certainty (animal health industry personal communication). The development of a new product results from a complex, long-term, expensive and multidisciplinary process. A project team is required, usually composed of a project leader and representatives of the following areas: marketing, manufacturing and controls guidance, regulatory affairs, finance, clinical studies and supply. Typically, the development process of an innovative product (based on a new mode-of-action active pharmaceutical ingredient) takes 10–15 years to be completed and costs around 30–40 million euros. The project team is responsible for the planning and execution of initiatives to ensure the product meets all regulatory requirements (quality, efficacy and animal/human/environment safety) and is granted official market authorization (animal health industry personal communication).

In the last 30 years, the animal health industry witnessed drastic changes concerning the development of new molecules or innovative products for parasite control. Technology advances (e.g. in structural biology, computational chemistry, structure-based drug design, genomics and proteomics) have accelerated the selection of new parasiticide candidates [173]. However, there is an increasing demand for eco-friendly ('green') products that reduce or eliminate parasites, without compromising safety or cost efficiency [173]. Indeed, new products are required to be safe not only for the target species but

Table 4 Clinical safety performed in 23 articles using essential oils (EOs) and essential oil compounds (EOCs) to control ticks in treated animals

Hosts	EOs/EOCs	Evaluated parameter				References
		Hemogram	Biochemistry	Clinical evaluation	Dermal evaluation	
Cattle	*C. citratus* e *C. nardus*	…	…	…	…	Chungsamarnyart and Jiwaginda [183]
Rabbits	*O. suave*	…	…	…	No adverse reaction	Mwangi et al. [135]
Cattle	*C. winteranius Jowitt*	…	No change	…	…	Martins and González [124]
Goats	*C. citratus* and *C. nardus*	…	…	No adverse reaction	No adverse reaction	John et al. [132]
Holstein cattle	*C. nardus*	No change	…	…	…	Agnolin et al. [157]
Holstein cattle	*C. nardus*	…	…	…	…	Agnolin et al. [184]
Sheep	*Th. trilobata*	…	…	…	…	Peebles et al. [134]
Holstein cattle	*Co. citriodora*	…	…	No adverse reaction	No adverse reaction	Olivo et al. [159]
Holstein cattle	*T. minuta*	…	…	…	No adverse reaction	Andreotti et al. [140]
Holstein cattle	*C. winterianus*	…	…	No adverse reaction	No adverse reaction	Agnolin et al. [141]
Holstein cattle	*Co. citriodora* and *Co. citriodora* modified	…	…	…	…	Chagas et al. [185]
Goats	*Ch. ambrosioides*	…	…	No adverse reaction	…	Kouam et al. [133]
Dogs (mixed breeds)	*T. minuta*	…	…	…	…	Silva et al. [130]
Holstein cattle	*M. alternifolia*	…	…	…	…	Boito et al. [125]
Holstein cattle	*Cinnamomum* sp.	…	…	…	…	Santos et al. [126]
Holstein cattle (calves)	Eugenol	…	…	No adverse reaction	No adverse reaction	Valente et al. [158]
Dogs (mixed breeds)	Lacecca® (*A. sativum*, + Allicin + *B. napus)*	No change	No change	No adverse reaction	No adverse reaction	Amer and Amer [131]
Baladi-Holstein cattle (cross breed)	Thymol and *E. globulus* combined with deltamethrin	…	No change	No adverse reaction	Allergic reaction in an animal	Arafa et al. [59]
Cocker Spaniel English dogs	Thymol + eugenol	No change	No change	No adverse reaction	No adverse reaction	Monteiro et al. [60]
Aberdeen-Angus cattle	Essentria® IC-3 (rosemary oil 10%, geraniol 5% and peppermint oil 2%)	…	…	No adverse reaction	…	Klafke et al. [142]
Simmental cattle	(*E*)-cinnamaldehyde	…	…	Sialorrhea and muscle tremors	No adverse reaction	Gonzaga et al. [21]
Girolando (Gyr × Holstein) cattle	*L. sidoides*	…	…	…	…	Pereira et al. [180]
Native breed cattle	*P. graveolens* L	…	…	No adverse reaction	No adverse reaction	Ibrahium et al. [143]

Abbreviations of the genera of plants: *Cymbopogon* (C.), *Ocimum* (O.), *Thelechitonia* (Th.), *Corymbia* (Co.), *Tagetes* (T.), *Chenopodium* (Ch.), *Melaleuca* (M.), *Allium* (A.), *Brassica* (B.), *Eucalyptus* (E.), *Lippia* (L.), *Pelargonium* (P.)

Evaluation not carried out

Clinical evaluation: Heart and respiratory rates, rectal and eyeball temperatures, dehydration and mucous membrane coloration changes

also for non-target species and the environment. According to the Food and Drugs Administration (FDA), there was a 2.7% increase in investments in research and development (R&D) by the industry from 1989 ($ 604 million) to 2017 ($ 1.1 billion). However, during the same period, the number of approvals of new molecules declined by 3.6% [174]. This highlights that, despite technological advances, the marketing authorization requirements for parasiticides have become more stringent [175].

The use of natural products to control ticks is a current trend since issues of sustainability, one health and animal welfare are increasingly present and permeation in society is necessary as soon as possible, whether in animal production or for companion animals (animal health industry personal communication). The availability of

EOs and EOCs based products on the veterinary market is currently limited. This may be related to several factors, including the lack of randomized clinical trials conducted according to current regulatory requirements for marketing authorization of products, whose efficacy has been demonstrated in laboratory studies only. In this regard, registration of new products is a lengthy process, and efficacy requirements may be excessively high. For example, the current Brazilian legislation for licensing anti-parasitic products for veterinary use dates to 1997 [119]. To be approved for the control of *R. microplus*, a product must present an average efficacy of at least 95% on 23 DPT in pen studies and on 7 and 14 DPT in field studies [119].

The in vitro acaricidal efficacy of EOs and EOCs is often promising. However, in vitro results are not always observed in field trials, especially in terms of persistent efficacy [176]. Perhaps, updated legislation with less stringent efficacy requirements could accelerate the marketing authorization of new products, including EOs and EOCs based products, which could be used for integrated tick management. There is a need for a broad discussion on the harmonization and efficacy requirements for these products, which should involve researchers, government agencies and industry. Another challenge related to the registration of EOs or EOCs based products is safety. While these products are usually believed to be eco-friendly, not all EOs and EOCs are innocuous to animals, harmless to the environment or leave no residues in meat and milk. Prolonged exposure to high concentrations of certain EOs can have deleterious effects on the behavior, health and welfare of the host [21, 147, 167, 177].

Other practical issues are linked to the supply, standardization and economic viability of EOs and EOCs. A reliable supply of affordable and standardized raw materials in sufficient amounts to meet the market demand can be a challenge for a product based on EOs or EOCs [178]. The secondary metabolism of a plant and EOs composition is directly affected by the soil acidity and climate (heat, photoperiod and humidity) [179]. Furthermore, most commonly, the biological effect of an EO is triggered by a composition of molecules (rather than one single compound), which raises the problem of how to perform the raw material quality check while not knowing all the substances that should be quantified. Consequently, the usual quality checkpoints during and at the end of the manufacturing process could also be tricky.

Regarding economic viability, the concentrations of EOs and EOCs that present efficacy are often high. This can make the production of a tick control product for cattle unfeasible, where 1 L of product needs to be diluted in large volumes of water (> 400 L) to allow treatment of multiple animals. For example, Pereira et al. [180], in a field study with *R. microplus*-infested cattle, observed an average effectiveness of 50%, reaching 63% on day 21, using *L. sidoides* EO at a concentration of 1% (10,000 ppm). This concentration is much higher than that found in commercially available spray products for control on cattle (generally > 1000 ppm) [21]. In tick control on dogs, a smaller amount of product is necessary to treat the animals, added to the fact that products for dogs are generally already available ready to use, without the need for dilution in large volumes of water.

Studies with structural modifications of EOCs [154, 181], development of formulations with nanotechnology [60, 125, 126] and combinations of botanical compounds [21, 59, 156, 182] with synthetic acaricides, as previously discussed, may be alternatives to solve these challenges, allowing the development of new technologies to control ticks on different animal species. In sum, despite the barriers mentioned, the animal health industry understands that the exploration of EOs and EOCs as a veterinary antiparasitic is an exciting endeavor (animal health industry personal communication).

Conclusions

This article provides a comprehensive review of the use of EOs and EOCs to reduce tick infestations on hosts and in the environment. Despite the research advances in this field of research, we conclude that there are still several research gaps and the urgent need for more randomized clinical trials that could allow the evaluation of the efficacy of EOs and EOCs based products for the control of ticks under field conditions. Future research should also consider the following critical points: (i) characterization of the EOs or description of the source, lot number and purity degree of the EOCs; (ii) standardization of the methods used to evaluate the efficacy of EOs and EOCs, following international guidelines (e.g. WAAVP guidelines) and national/regional regulatory agencies; (iii) formulation development, especially using nanotechnology and encapsulation, allowing to reduce the volatility of EOs and EOCs, which may increase efficacy and safety; (iv) evaluation of EOs and EOCs safety for target and non-target animals and the environment. Finally, (v) studies assessing the efficacy of synthetic acaricides already in the market in combination with EOs or EOCs could provide valuable information on their synergistic activity against ticks and usefulness from an integrated tick management perspective.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13071-023-05969-w.

Additional file 1. Botanical species used to extract essential oils and compounds present in essential oils that were used in field and semi-field studies to control ticks.

Acknowledgements
Not applicable.

Author contributions
BCFG: Writing of the text, critical analysis, studies selection, data extraction and risk of bias assessment. MMB: Selection of articles, reading and critical analysis. ALC: Selection of articles, reading and critical analysis. LJMPS: Selection of articles, reading and critical analysis. FLV: Selection of articles, reading and critical analysis. LM: Selection of articles, reading and critical analysis. PM: Critical analysis, studies selection, data extraction and risk of bias assessment. DCR: Industry point of view. EDFS: Industry point of view. GAS: Industry point of view. LMC-J: Critical analysis of the material. LLF: Translation, critical analysis of the material and review. WDZL: Critical analysis of the material. CM: General coordinator, critical analysis of the material, studies selection, data extraction and risk of bias assessment and review.

Funding
We thank the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the financial support (project financing and grants) and for the grants PQ to C. Monteiro (317482/2021-1), L.M. Costa-Junior (306059/2022-3) and W.D.Z. Lopes (307733/2021-1). This study also was financed (scholarships) in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brazil (CAPES)—Finance Code 001" and FAPEG (202110267000294).

Availability of data and materials
The data that support the findings of this study are available in the references information of this article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Some of the authors of this article are employees of: Ourofino Animal Helth (E.D.F. Souza), Merck/MSD Animal Health (D.C. Rodrigues) and Boehringer Ingelheim Animal Health (G.A. Sabatini). However, there were no conflicting interests that may have biased the work reported in this paper.

Author details
[1]Programa de Pós-graduação em Ciência Animal - Escola de Veterinária e Zootecnia, Universidade Federal de Goiás, Rodovia Goiânia - Nova Veneza, Km 8, Campus Samambaia, Goiânia, GO 74690-900, Brasil. [2]Faculdade de Medicina, Universidade Federal de Goiás, Campus Colemar Natal e Silva, Rua 235, s/n, Setor Leste Universitário, Goiânia, GO 74605-050, Brasil. [3]Programa de Pós-Graduação em Ciências Farmacêuticas - Faculdade de Farmácia, Universidade Federal de Goiás, Praça Universitária, no. 1166, Setor Universitário, Goiânia, GO 74605-220, Brasil. [4]MSD Saúde Animal, Avenida Dr. Chucri Zaidan, 246-96, 9º Andar, São Paulo, SP 04583-110, Brasil. [5]Ourofino Saúde Animal, Rodovia Anhanguera, Km 330, Distrito Industrial, Ribeirão Preto, SP 14140-000, Brasil. [6]Boehringer Ingelheim Animal Health, Binger Strasse 173, 55218 Ingelheim, Germany. [7]Centro de Pesquisas do CCBS, Universidade Federal do Maranhão, Avenida dos Portugueses, no. 1966, São Luís, MA 65080-805, Brasil. [8]Departamento de Medicina Veterinária Preventiva - Escola de Veterinária, Universidade Federal de Minas Gerais, Av. Antônio Carlos, no. 6627, Campus Pampulha, Belo Horizonte, MG 31270-901, Brasil. [9]Departamento de Biociências e Tecnologia - Instituto de Patologia Tropical e de Saúde Pública, Universidade Federal de Goiás-, Campus Colemar Natal e Silva - Rua 235, s/n - Setor Leste Universitário, Goiânia, GO 74605-050, Brasil.

Received: 18 May 2023 Accepted: 12 September 2023
Published online: 14 November 2023

References

1. Jonsson NN. The productivity effects of cattle tick (*Boophilus microplus*) infestation on cattle, with particular reference to *Bos indicus* cattle and their crosses. Vet Parasitol. 2006;137:1–10. https://doi.org/10.1016/j.vetpar.2006.01.010.
2. Grisi L, Leite RC, Martins JRS, de Barros ATM, Andreotti R, Cançado PHD, et al. Reassessment of the potential economic impact of cattle parasites in Brazil. Rev Bras Parasitol Vet. 2014;23:150–6. https://doi.org/10.1590/S1984-29612014042.
3. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food security: the challenge of feeding 9 billion people. Science. 2010;327:812–8. https://doi.org/10.1126/science.1185383.
4. King T, Cole M, Farber JM, Eisenbrand G, Zabaras D, Fox EM, et al. Food safety for food security: relationship between global megatrends and developments in food safety. Trends Food Sci Technol. 2017;68:160–75. https://doi.org/10.1016/j.tifs.2017.08.014.
5. Shaw SE, Day MJ, Birtles RJ, Breitschwerdt EB. Tick-borne infectious diseases of dogs. Trends Parasitol. 2001;17:74–80. https://doi.org/10.1016/S1471-4922(00)01856-0.
6. Dantas-Torres F. Biology and ecology of the brown dog tick *Rhipicephalus sanguineus*. Parasit Vectors. 2010;3:26. https://doi.org/10.1186/1756-3305-3-26.
7. Tutija JF, Soares RL, Echeverria JT, Souza MAS, Silva TOV, Ramos RAN, et al. Microfilaremia by *Cercopithifilaria bainae* in a dog from the central western region of Brazil: case report. Arq Bras Med Vet e Zootec. 2020;72:312–6. https://doi.org/10.1590/1678-4162-11177.
8. Growth from Knowledge. Man's best friend: global pet ownership and feeding trends. 2016. https://www.gfk.com/insights/mans-best-friend-global-pet-ownership-and-feeding-trends. Accessed 29 Jun 2021.
9. Irvine L, Cilia L. More-than-human families: pets, people, and practices in multispecies households. Sociol Compass. 2017;11:e12455. https://doi.org/10.1111/soc4.12455.
10. Jones EH, Hinckley AF, Hook SA, Meek JI, Backenson B, Kugeler KJ, et al. Pet ownership increases human risk of encountering ticks. Zoonoses Public Health. 2018;65:74–9. https://doi.org/10.1111/zph.12369.
11. Skotarczak B. The role of companion animals in the environmental circulation of tick-borne bacterial pathogens. Ann Agric Environ Med. 2018;25:473–80. https://doi.org/10.26444/aaem/93381.
12. Madison-Antenucci S, Kramer LD, Gebhardt LL, Kauffman E. Emerging tick-borne diseases. Clin Microbiol Rev. 2020;33:e000083-18. https://doi.org/10.1128/CMR.00083-18.
13. Adenubi OT, Ahmed AS, Fasina FO, McGaw LJ, Eloff JN, Naidoo V. Pesticidal plants as a possible alternative to synthetic acaricides in tick control: a systematic review and meta-analysis. Ind Crops Prod. 2018;123:779–806. https://doi.org/10.1016/j.indcrop.2018.06.075.
14. Salman M, Abbas RZ, Israr M, Abbas A, Mehmood K, Khan MK, et al. Repellent and acaricidal activity of essential oils and their components against Rhipicephalus ticks in cattle. Vet Parasitol. 2020;283:109178. https://doi.org/10.1016/j.vetpar.2020.109178.
15. Agwunobi DO, Yu Z, Liu J. A retrospective review on ixodid tick resistance against synthetic acaricides: implications and perspectives for future resistance prevention and mitigation. Pestic Biochem Physiol. 2021;173:104776. https://doi.org/10.1016/j.pestbp.2021.104776.
16. Furlong J, Martins JR, Prata MCA. O carrapato dos bovinos e a resistência: temos o que comemorar? A Hora Veterinária. 2007;159:1–7.
17. Reck J, Klafke GM, Webster A, DallAgnol B, Scheffer R, Souza UA, et al. First report of fluazuron resistance in *Rhipicephalus microplus*: a field tick population resistant to six classes of acaricides. Vet Parasitol. 2014;201:128–36. https://doi.org/10.1016/j.vetpar.2014.01.012.
18. Klafke G, Webster A, DallAgnol B, Pradel E, Silva J, de La Canal LH, et al. Multiple resistance to acaricides in field populations of *Rhipicephalus microplus* from Rio Grande do Sul state. Southern Brazil Ticks Tick Borne Dis. 2017;8:73–80. https://doi.org/10.1016/j.ttbdis.2016.09.019.
19. Godara R, Katoch R, Rafiqi SI, Yadav A, Nazim K, Sharma R, et al. Synthetic pyrethroid resistance in *Rhipicephalus* (*Boophilus*) *microplus*

ticks from north-western Himalayas. India Trop Anim Health Prod. 2019;51:1203–8. https://doi.org/10.1007/s11250-019-01810-8.
20. Valsoni LM, Freitas MG de, Echeverria JT, Borges DGL, Tutija J, Borges F de A. Resistance to all chemical groups of acaricides in a single isolate of *Rhipicephalus microplus* in Mato Grosso do Sul, Brazil. Int. J. Acarol. 2020;46:276–80. https://doi.org/10.1080/01647954.2020.1765867
21. Gonzaga BCF, de Moraes NR, Gomes GW, Coutinho AL, Vale FL, Sousa LJMP, et al. Combination of synthetic acaricides with (*E*)-cinnamaldehyde to control *Rhipicephalus microplus*. Exp Appl Acarol. 2022;88:191–207. https://doi.org/10.1007/s10493-022-00743-6.
22. Miller RJ, George JE, Guerrero F, Carpenter L, Welch JB. Characterization of acaricide resistance in *Rhipicephalus sanguineus* (Latreille) (Acari: Ixodidae) collected from the Corozal Army Veterinary Quarantine Center. Panama J Med Entomol. 2001;38:298–302. https://doi.org/10.1603/0022-2585-38.2.298.
23. Rodriguez-Vivas RI, Ojeda-Chi MM, Trinidad-Martinez I, Pérez de León AA. First documentation of ivermectin resistance in *Rhipicephalus sanguineus* sensu lato (Acari: Ixodidae). Vet Parasitol. 2017;233:9–13. https://doi.org/10.1016/j.vetpar.2016.11.015.
24. Rodriguez-Vivas RI, Ojeda-Chi MM, Trinidad-Martinez I, Bolio-González ME. First report of amitraz and cypermethrin resistance in *Rhipicephalus sanguineus* sensu lato infesting dogs in Mexico. Med Vet Entomol. 2017;31:72–7. https://doi.org/10.1111/mve.12207.
25. Ziapour SP, Kheiri S, Asgarian F, Fazeli-Dinan M, Yazdi F, Mohammadpour RA, et al. First report of pyrethroid resistance in *Rhipicephalus* (*Boophilus*) *annulatus* larvae (Say, 1821) from Iran. Acta Trop. 2016;156:22–9. https://doi.org/10.1016/j.actatropica.2016.01.001.
26. Ziapour SP, Kheiri S, Fazeli-Dinan M, Sahraei-Rostami F, Mohammadpour RA, Aarabi M, et al. Pyrethroid resistance in Iranian field populations of *Rhipicephalus* (*Boophilus*) *annulatus*. Pestic Biochem Physiol. 2017;136:70–9. https://doi.org/10.1016/j.pestbp.2016.08.001.
27. Aboelhadid SM, Arafa WM, Mahrous LN, Fahmy MM, Kamel AA. Molecular detection of *Rhipicephalus* (*Boophilus*) *annulatus* resistance against deltamethrin in middle Egypt. Vet Parasitol Reg Stud Reports. 2018;13:198–204. https://doi.org/10.1016/j.vprsr.2018.06.008.
28. El-Ashram S, Aboelhadid SM, Kamel AA, Mahrous LN, Fahmy MM. First report of cattle tick *Rhipicephalus* (*Boophilus*) *annulatus* in Egypt resistant to ivermectin. Insects. 2019;10:404. https://doi.org/10.3390/insects10110404.
29. Arafa WM, Aboelhadid SM, Moawad A, Shokeir KM, Ahmed O. Toxicity, repellency and anti-cholinesterase activities of thymol-eucalyptus combinations against phenotypically resistant *Rhipicephalus annulatus* ticks. Exp Appl Acarol. 2020;81:265–77. https://doi.org/10.1007/s10493-020-00506-1.
30. Vudriko P, Umemiya-Shirafuji R, Okwee-Acai J, Tayebwa DS, Byaruhanga J, Jirapattharasate C, et al. Genetic mutations in sodium channel domain II and carboxylesterase genes associated with phenotypic resistance against synthetic pyrethroids by *Rhipicephalus* (*Boophilus*) *decoloratus* ticks in Uganda. Pestic Biochem Physiol. 2017;143:181–90. https://doi.org/10.1016/j.pestbp.2017.07.009.
31. Jyoti S, Singh NK, Singh H, Rath SS. Modified larval packet test based detection of amitraz resistance in *Hyalomma anatolicum* Koch (Acari: Ixodidae) from Punjab districts of India. Int J Acarol. 2019;45:391–4. https://doi.org/10.1080/01647954.2019.1667432.
32. Chagas ACS. Controle de parasitas utilizando extratos vegetais. Rev Bras Parasitol Vet. 2004;13:156–60.
33. Isman MB. Perspective Botanical insecticides: for richer, for poorer. Pest Manag Sci. 2008;64:8–11. https://doi.org/10.1002/ps.1470
34. Borges LMF, de Sousa LAD, da Silva Barbosa C. Perspectives for the use of plant extracts to control the cattle tick *Rhipicephalus* (*Boophilus*) *microplus*. Rev Bras Parasitol Vet. 2011;20:89–96. https://doi.org/10.1590/s1984-29612011000200001.
35. Pavela R, Benelli G. Essential oils as ecofriendly biopesticides? Challenges and constraints. Trends Plant Sci. 2016;21:1000–7. https://doi.org/10.1016/j.tplants.2016.10.005.
36. Bakkali F, Averbeck S, Averbeck D, Idaomar M. Biological effects of essential oils - A review. Food Chem Toxicol. 2008;46:446–75. https://doi.org/10.1016/j.fct.2007.09.106.
37. Yap PSX, Yiap BC, Ping HC, Lim SHE. Essential oils, a new horizon in combating bacterial antibiotic resistance. Open Microbiol J. 2014;8:6–14. https://doi.org/10.2174/1874285801408010006.
38. Aljaafari MN, AlAli AO, Baqais L, Alqubaisy M, AlAli M, Molouki A, et al. An overview of the potential therapeutic applications of essential oils. Molecules. 2021;26:628. https://doi.org/10.3390/molecules26030628.
39. Asbahani A El, Miladi K, Badri W, Sala M, Addi EHA, Casabianca H, et al. Essential oils: from extraction to encapsulation. Int J Pharm. 2015;483:220–43. https://doi.org/10.1016/j.ijpharm.2014.12.069.
40. Ndungu M, Lwande W, Hassanali A, Moreka L, Chhabra SC. *Cleome monophylla* essential oil and its constituents as tick (*Rhipicephalus appendiculatus*) and maize weevil (*Sitophilus zeamais*) repellents. Entomol Exp Appl. 1995;76:217–22.
41. Brown HA, Minott DA, Ingram CW, Williams LAD. Biological activities of the extracts and constituents of Pimento, *Pimenta dioica* L against the southern cattle tick *Boophilus microplus*. Insect Sci. 1998;18:9–16. https://doi.org/10.1017/s1742758400007402.
42. Lwande W, Ndakala AJ, Hassanali A, Moreka L, Nyandat E, Ndungu M, et al. *Gynandropsis gynandra* essential oil and its constituents as tick (*Rhipicephalus appendiculatus*) repellents. Phytochemistry. 1999;50:401–5. https://doi.org/10.1016/S0031-9422(98)00507-X.
43. Prates HT, Leite RC, Craveiro AA, Oliveira AB. Identification of some chemical components of the essential oil from molasses grass (*Melinis minutiflora* Beauv) and their activity against cattle-tick (*Boophilus microplus*). J Braz Chem Soc. 1998;9:193–7. https://doi.org/10.1590/S0103-50531998000200013.
44. Soares SF, Borges LM, de Sousa BR, Ferreira LL, Louly CC, Tresvenzol LM, et al. Repellent activity of plant-derived compounds against *Amblyomma cajennense* (Acari: Ixodidae) nymphs. Vet Parasitol. 2010;167:67–73. https://doi.org/10.1016/j.vetpar.2009.09.047.
45. Gomes GA, Monteiro CMO, Senra TOS, Zeringota V, Calmon F, Matos RDS, et al. Chemical composition and acaricidal activity of essential oil from *Lippia sidoides* on larvae of *Dermacentor nitens* (Acari: Ixodidae) and larvae and engorged females of *Rhipicephalus microplus* (Acari: Ixodidae). Parasitol Res. 2012;111:2423–30. https://doi.org/10.1007/s00436-012-3101-9.
46. Lage TCDA, Montanari RM, Fernandes SA, Monteiro CMO, Senra TOS, Zeringota V, et al. Activity of essential oil of *Lippia triplinervis* Gardner (Verbenaceae) on *Rhipicephalus microplus* (Acari: Ixodidae). Parasitol Res. 2013;112:863–9. https://doi.org/10.1007/s00436-012-3209-y.
47. Gomes GA, Monteiro CMO, Julião LS, Maturano R, Senra TOS, Zeringóta V, et al. Acaricidal activity of essential oil from *Lippia sidoides* on unengorged larvae and nymphs of *Rhipicephalus sanguineus* (Acari: Ixodidae) and *Amblyomma cajennense* (Acari: Ixodidae). Exp Parasitol. 2014;137:41–5. https://doi.org/10.1016/j.exppara.2013.12.003.
48. Lage TCA, Montanari RM, Fernandes SA, Monteiro CMO, Senra TOS, Zeringota V, et al. Chemical composition and acaricidal activity of the essential oil of *Baccharis dracunculifolia* De Candole (1836) and its constituents nerolidol and limonene on larvae and engorged females of *Rhipicephalus microplus* (Acari: Ixodidae). Exp Parasitol. 2015;148:24–9. https://doi.org/10.1016/j.exppara.2014.10.011.
49. Delmonte C, Cruz PB, Zeringóta V, de Mello V, Ferreira F, Amaral MPH, et al. Evaluation of the acaricidal activity of thymol incorporated in two formulations for topical use against immature stages of *Rhipicephalus sanguineus* sensu lato (Latreille, 1806) (Acari: Ixodidae). Parasitol Res. 2017;116:2957–64. https://doi.org/10.1007/s00436-017-5604-x.
50. Ferreira FM, Delmonte CC, Novato TLP, Monteiro CMO, Daemon E, Vilela FMP, et al. Acaricidal activity of essential oil of *Syzygium aromaticum*, hydrolate and eugenol formulated or free on larvae and engorged females of *Rhipicephalus microplus*. Med Vet Entomol. 2018;32:41–7. https://doi.org/10.1111/mve.12259.
51. Barrozo MM, Zeringóta V, Borges LMF, Moraes N, Benz K, Farr A, et al. Repellent and acaricidal activity of coconut oil fatty acids and their derivative compounds and catnip oil against *Amblyomma sculptum*. Vet Parasitol. 2021;300:109591. https://doi.org/10.1016/j.vetpar.2021.109591.
52. Matos RS, Daemon E, Monteiro CMO, Sampieri BR, Marchesini PBC, Delmonte C, et al. Thymol action on cells and tissues of the synganglia and salivary glands of *Rhipicephalus sanguineus* sensu lato females (Acari: Ixodidae). Ticks Tick Borne Dis. 2019;10:314–20. https://doi.org/10.1016/j.ttbdis.2018.11.003.
53. Matos RS, de Oliveira PR, Coelho L, de Paula LGF, Zeringota V, Carvalho Silva B, et al. Thymol: effects on reproductive biology and Gene's organ morphology in *Rhipicephalus sanguineus* sensu lato engorged females

(Acari: Ixodidae). Ticks Tick Borne Dis. 2020;11:101308. https://doi.org/10.1016/j.ttbdis.2019.101308.

54. Marchesini P, Lemos ASO, Bitencourt ROB, Fiorotti J, Angelo IC, Fabri RL, et al. Assessment of lipid profile in fat body and eggs of *Rhipicephalus microplus* engorged females exposed to (*E*)-cinnamaldehyde and α-bisabolol, potential acaricide compounds. Vet Parasitol. 2021;300:109596. https://doi.org/10.1016/j.vetpar.2021.109596.
55. Penha T, Costa ACC, da Silva Lima A, Camargo-Mathias MI, Blank AF, Abreu-Silva AL, et al. Effects of acaricidal essential oils from *Lippia sidoides* and *Lippia gracilis* and their main components on vitellogenesis in *Rhipicephalus microplus* (Canestrini, 1888) (Acari: Ixodidae). Vet Parasitol. 2021;299:109584. https://doi.org/10.1016/j.vetpar.2021.109584.
56. Santos EGG, Bezerra WADS, Temeyer KB, León AAP, Costa-Junior LM, Soares AMDS. Effects of essential oils on native and recombinant acetylcholinesterases of *Rhipicephalus microplus*. Brazilian J Vet Parasitol. 2021;30:e002221. https://doi.org/10.1590/S1984-29612021024.
57. Tavares CP, Sabadin GA, Sousa IC, Gomes MN, Soares AMS, Monteiro CMO, et al. Effects of carvacrol and thymol on the antioxidant and detoxifying enzymes of *Rhipicephalus microplus* (Acari: Ixodidae). Ticks Tick Borne Dis. 2022;13:101929. https://doi.org/10.1016/j.ttbdis.2022.101929.
58. Coelho L, de Paula LGF, Alves SGA, Sampaio ALN, Bezerra GP, Vilela FMP, et al. Combination of thymol and eugenol for the control of *Rhipicephalus sanguineus* sensu lato: evaluation of synergism on immature stages and formulation development. Vet Parasitol. 2020;277:108989. https://doi.org/10.1016/j.vetpar.2019.108989.
59. Arafa WM, Aboelhadid SM, Moawad A, Shokeir KM, Ahmed O, Pérez de León AA. Control of *Rhipicephalus annulatus* resistant to deltamethrin by spraying infested cattle with synergistic eucalyptus essential oil-thymol-deltamethrin combination. Vet Parasitol. 2021;290:109346. https://doi.org/10.1016/j.vetpar.2021.109346.
60. Monteiro C, Ferreira LL, de Paula LGF, de Oliveira Filho JG, de Oliveira SF, Muniz ER, et al. Thymol and eugenol microemulsion for *Rhipicephalus sanguineus* sensu lato control: formulation development, field efficacy, and safety on dogs. Vet Parasitol. 2021;296:109501. https://doi.org/10.1016/j.vetpar.2021.109501.
61. Ellse L, Wall R. The use of essential oils in veterinary ectoparasite control: a review. Med Vet Entomol. 2014;28:233–43. https://doi.org/10.1111/mve.12033.
62. Adenubi OT, Fasina FO, McGaw LJ, Eloff JN, Naidoo V. Plant extracts to control ticks of veterinary and medical importance: a review. South African J Bot. 2016;105:178–93. https://doi.org/10.1016/j.sajb.2016.03.010.
63. Rosado-Aguilar JA, Arjona-Cambranes K, Torres-Acosta JFJ, Rodríguez-Vivas RI, Bolio-González ME, Ortega-Pacheco A, et al. Plant products and secondary metabolites with acaricide activity against ticks. Vet Parasitol. 2017;238:66–76. https://doi.org/10.1016/j.vetpar.2017.03.023.
64. Benelli G, Pavela R. Repellence of essential oils and selected compounds against ticks - A systematic review. Acta Trop. 2018;179:47–54. https://doi.org/10.1016/j.actatropica.2017.12.025.
65. Nwanade CF, Wang M, Wang T, Yu Z, Liu J. Botanical acaricides and repellents in tick control: current status and future directions. Exp Appl Acarol. 2020;81:1–35. https://doi.org/10.1007/s10493-020-00489-z.
66. Nwanade CF, Yu Z, Liu J. Botanical acaricides induced morphophysiological changes of reproductive and salivary glands in tick: a mini-review. Res Vet Sci. 2020;132:285–91. https://doi.org/10.1016/j.rvsc.2020.07.008.
67. Rodríguez-Vivas RI, Rivas AL, Chowell G, Fragoso SH, Rosario CR, García Z, et al. Spatial distribution of acaricide profiles (*Boophilus microplus* strains susceptible or resistant to acaricides) in southeastern Mexico. Vet Parasitol. 2007;146:158–69. https://doi.org/10.1016/j.vetpar.2007.01.016.
68. Vilela VLR, Feitosa TF, Bezerra RA, Klafke GM, Riet-Correa F. Multiple acaricide-resistant *Rhipicephalus microplus* in the semi-arid region of Paraíba State. Brazil Ticks Tick Borne Dis. 2020;11:101413. https://doi.org/10.1016/j.ttbdis.2020.101413.
69. Fernández-Salas A, Rodríguez-Vivas RI, Alonso-Díaz MA. First report of a *Rhipicephalus microplus* tick population multi-resistant to acaricides and ivermectin in the Mexican tropics. Vet Parasitol. 2012;183:338–42. https://doi.org/10.1016/j.vetpar.2011.07.028.
70. Cuore U, Solari MA. Poblaciones multirresistentes de garrapatas. Vet. 2014;50:4–13.
71. Higa LOS, Garcia MV, Barros JC, Koller WW, Andreotti R. Acaricide resistance status of the *Rhipicephalus microplus* in Brazil: a literature overview. Med Chem. 2015;5:326–33. https://doi.org/10.4172/2161-0444.1000281.
72. Petermann J, Cauquil L, Hurlin JC, Gaia H, Hüe T. Survey of cattle tick, *Rhipicephalus* (*Boophilus*) *microplus*, resistance to amitraz and deltamethrin in New Caledonia. Vet Parasitol. 2016;217:64–70. https://doi.org/10.1016/j.vetpar.2015.12.010.
73. Fular A, Sharma AK, Kumar S, Nagar G, Chigure G, Ray DD, et al. Establishment of a multi-acaricide resistant reference tick strain (IVRI-V) of *Rhipicephalus microplus*. Ticks Tick Borne Dis. 2018;9:1184–91. https://doi.org/10.1016/j.ttbdis.2018.04.014.
74. Cavalcante ASA, Ferreira LL, Couto LFM, Zapa DMB, Heller LM, Nicaretta JE, et al. An update on amitraz efficacy against *Rhipicephalus microplus* after 15 years of disuse. Parasitol Res. 2021;120:1103–8. https://doi.org/10.1007/s00436-021-07063-5.
75. Kumar R, Sharma AK, Kumar S, Nagar G, Ranjan R, Kumar S, et al. Resistance of *Rhipicephalus microplus* ticks against synthetic pyrethroids from different places of Rewa district of Madhya Pradesh. India Int J Trop Insect Sci. 2022;42:2393–402. https://doi.org/10.1007/s42690-022-00767-w.
76. Borges LMF, Soares FS, Fonseca IN, Chaves VV, Louly CCB. Resistência acaricida em larvas de *Rhipicephalus sanguineus* (Acari: Ixodidae) de Goiânia-GO, Brasil. Rev Patol Trop. 2007;36:87–95.
77. Eiden AL, Kaufman PE, Oi FM, Allan SA, Miller RJ. Detection of permethrin resistance and fipronil tolerance in *Rhipicephalus sanguineus* (Acari: Ixodidae) in the United States. J Med Entomol. 2015;52:429–36. https://doi.org/10.1093/jme/tjv005.
78. Becker S, Webster A, Doyle RL, Martins JR, Reck J, Klafke GM. Resistance to deltamethrin, fipronil and ivermectin in the brown dog tick, *Rhipicephalus sanguineus* sensu stricto, Latreille (Acari: Ixodidae). Ticks Tick Borne Dis. 2019;10:1046–50. https://doi.org/10.1016/j.ttbdis.2019.05.015.
79. Tucker NSG, Weeks ENI, Kaufman PE. Prevalence and distribution of pathogen infection and permethrin resistance in tropical and temperate populations of *Rhipicephalus sanguineus* s.l. collected worldwide. Med Vet Entomol. 2021;35:147–57. https://doi.org/10.1111/mve.12479.
80. Heath ACG, Levot GW. Parasiticide resistance in flies, lice and ticks in New Zealand and Australia: mechanisms, prevalence and prevention. N Z Vet J. 2015;63:199–210. https://doi.org/10.1080/00480169.2014.960500.
81. Dzemo WD, Thekisoe O, Vudriko P. Development of acaricide resistance in tick populations of cattle: A systematic review and meta-analysis. Heliyon 2022;8:e08718. https://doi.org/10.1016/j.heliyon.2022.e08718
82. Brasil. Principais resultados - 2021, Pesquisa de Pecuária Municipal. IBGE. 2021.
83. USDA. Livestock and poultry: world markets and trade, United States Department of Agriculture and Foreign Agricultural Service. 2022.
84. FAOSTAT. Crops and livestock products, Production of raw milk of cattle: top 10 producers 2021. 2022.
85. Abinpet. População de animais de estimação no Brasil - 2013. São Paulo. 2013 https://www.gov.br/agricultura/pt-br/assuntos/camaras-setoriais-tematicas/documentos/camaras-tematicas/insumos-agropecuarios/anos-anteriores/ibge-populacao-de-animais-de-estimacao-no-brasil-2013-abinpet-79.pdf/view Accessed 12 Sept 2022.
86. Abinpet. Mercado Pet Brasil 2022. São Paulo. 2022 https://abinpet.org.br/wp-content/uploads/2022/08/abinpet_folder_dados_mercado_2022_draft3_web.pdf Accessed 12 Sept 2022.
87. BFG (The Brazil Flora Group). Flora do Brasil 2020. Jardim Botânico do Rio de Janeiro, Rio de Janeiro. 2021 p. 1–28. https://doi.org/10.47871/jbrj2021001
88. Martins J, Furlong J, Leite RC. Controle de carrapatos, in: barros-Battesti DM, Arzua M, Bechara GH, editors. Carrapatos de importância médico-veterinária da região neotropical: Um guia ilustrado para identificaçãode espécies. São Paulo: Vox/ICTTD-3/Butantan; 2006 p. 145–54.
89. Rodriguez-Vivas RI, Grisi L, Pérez de León AA, Silva Villela H, Torres-Acosta JFJ, Fragoso Sánchez H, et al. Potential economic impact assessment for cattle parasites in Mexico. Review. Rev Mex Cienc Pec. 2017;8:61–74. https://doi.org/10.22319/rmcp.v8i1.4305

90. Higa LOS, Garcia MV, Barros JC, Koller WW, Andreotti R. Evaluation of *Rhipicephalus* (*Boophilus*) *microplus* (Acari: Ixodidae) resistance to different acaricide formulations using samples from Brazilian properties. Rev Bras Parasitol Vet. 2016;25:163–71. https://doi.org/10.1590/S1984-29612016026.
91. Rodriguez-Vivas RI, Jonsson NN, Bhushan C. Strategies for the control of *Rhipicephalus microplus* ticks in a world of conventional acaricide and macrocyclic lactone resistance. Parasitol Res. 2018;117:3–29. https://doi.org/10.1007/s00436-017-5677-6.
92. Marchesini P, Novato TP, Cardoso SJ, de Azevedo Prata MC, Nascimento RM, Klafke G, et al. Acaricidal activity of (*E*)-cinnamaldehyde and α-bisabolol on populations of *Rhipicephalus microplus* (Acari: Ixodidae) with different resistance profiles. Vet Parasitol. 2020;286:109226. https://doi.org/10.1016/j.vetpar.2020.109226.
93. Spach DH, Liles WC, Campbell GL, Quick RE, Anderson DE, Fritsche TR. Tick-borne diseases in the United States. N Engl J Med. 1993;329:936–47. https://doi.org/10.1056/NEJM199309233291308.
94. Piesman J, Eisen L. Prevention of tick-borne diseases. Annu Rev Entomol. 2008;53:323–43. https://doi.org/10.1146/annurev.ento.53.103106.093429.
95. Pfäffle M, Littwin N, Muders SV, Petney TN. The ecology of tick-borne diseases. Int J Parasitol. 2013;43:1059–77. https://doi.org/10.1016/j.ijpara.2013.06.009.
96. Dantas-Torres F. The brown dog tick, *Rhipicephalus sanguineus* (Latreille, 1806) (Acari: Ixodidae): From taxonomy to control. Vet Parasitol. 2008;152:173–85. https://doi.org/10.1016/j.vetpar.2007.12.030.
97. Matsumoto K, Brouqui P, Raoult D, Parola P. Experimental infection models of ticks of the *Rhipicephalus sanguineus* group with *Rickettsia conori*. Vector-borne Zoonotic Dis. 2005;5:363–72. https://doi.org/10.1089/vbz.2005.5.363.
98. Dantas-Torres F, Figueredo LA, Brandão-Filho SP. *Rhipicephalus sanguineus* (Acari: Ixodidae), the brown dog tick, parasitizing humans in Brazil. Rev Soc Bras Med Trop. 2006;39:64–7. https://doi.org/10.1590/S0037-86822006000100012.
99. Demma LJ, Traeger MS, Nicholson WL, Paddock CD, Blau DM, Eremeeva ME, et al. Rocky mountain spotted fever from an unexpected tick vector in Arizona. N Engl J Med. 2005;353:587–94. https://doi.org/10.1056/NEJMoa050043.
100. Guglielmone AA, Beati L, Barros-Battesti DM, Labruna MB, Nava S, Venzal JM, et al. Ticks (Ixodidae) on humans in South America. Exp Appl Acarol. 2006;40:83–100. https://doi.org/10.1007/s10493-006-9027-0.
101. Dantas-Torres F, Chomel BB, Otranto D. Ticks and tick-borne diseases: a one health perspective. Trends Parasitol. 2012;28:437–46. https://doi.org/10.1016/j.pt.2012.07.003.
102. Dantas-Torres F, Otranto D. Further thoughts on the taxonomy and vector role of *Rhipicephalus sanguineus* group ticks. Vet Parasitol. 2015;208:9–13. https://doi.org/10.1016/j.vetpar.2014.12.014.
103. Pérez de León AA, Teel PD, Auclair AN, Messenger MT, Guerrero FD, Schuster G, et al. Integrated strategy for sustainable cattle fever tick eradication in USA is required to mitigate the impact of global change. Front Physiol. 2012;3:195. https://doi.org/10.3389/fphys.2012.00195.
104. D'Amico G, Mihalca AD, Estrada-Peña A. *Rhipicephalus annulatus* (Say, 1821) (Figs. 133–135). In: estrada-Peña A, Mihalca A, Petney T, editors. Ticks of Europe and North Africa. Springer, Cham. 2017 p. 335–42. https://doi.org/10.1007/978-3-319-63760-0_64
105. Walker AR, Bouattour A, Camicas JL, Estrada-Peña A, Horak IG, Latif AA, et al. Ticks of domestic animals in Africa: a guide to identification of species. Edinburg Scotland, U.K.: Biosciences Reports; 2014.
106. Nava S, Beati L, Labruna MB, Cáceres AG, Mangold AJ, Guglielmone AA. Reassessment of the taxonomic status of *Amblyomma cajennense* (Fabricius, 1787) with the description of three new species, *Amblyomma tonelliae* n. sp., *Amblyomma interandinum* n. sp. and *Amblyomma patinoi* n. sp., and reinstatement of *Amblyomma mixtum* Koch, 1844, and *Amblyomma sculptum* Berlese, 1888 (Ixodida: Ixodidae). Ticks Tick Born Dis. 2014;5:252–76. https://doi.org/10.1016/j.ttbdis.2013.11.004.
107. Ghosh S, Nagar G. Problem of ticks and tick-borne diseases in India with special emphasis on progress in tick control research: a review. J Vector Borne Dis. 2014;51:259–70.
108. Cruz EMO, Costa-Junior LM, Pinto JAO, Santos DA, de Araujo SA, Arrigoni-Blank MF, et al. Acaricidal activity of *Lippia gracilis* essential oil and its major constituents on the tick *Rhipicephalus* (*Boophilus*) *microplus*. Vet Parasitol. 2013;195:198–202. https://doi.org/10.1016/j.vetpar.2012.12.046.
109. De Sousa LAD, Da Costa DP, Ferri PH, Showler AT, Borges LMF. Soil quality influences efficacy of *melia azedarach* (Sapindales: Meliaceae), fruit extracts against *Rhipicephalus* (*Boophilus*) *microplus* (Acari: Ixodidae). Ann Entomol Soc Am. 2014;107:484–9. https://doi.org/10.1603/AN13167.
110. George DR, Finn RD, Graham KM, Sparagano OAE. Present and future potential of plant-derived products to control arthropods of veterinary and medical significance. Parasites Vectors. 2014;7:28. https://doi.org/10.1186/1756-3305-7-28.
111. Silva Lima A, Milhomem MN, Santos Monteiro O, Arruda ACP, de Castro JAM, Fernandes YML, et al. Seasonal analysis and acaricidal activity of the thymol-type essential oil of *Ocimum gratissimum* and its major constituents against *Rhipicephalus microplus* (Acari: Ixodidae). Parasitol Res. 2018;117:59–65. https://doi.org/10.1007/s00436-017-5662-0.
112. Peixoto MG, Costa-Júnior LM, Blank AF, Lima AS, Menezes TSA, Santos DA, et al. Acaricidal activity of essential oils from *Lippia alba* genotypes and its major components carvone, limonene, and citral against *Rhipicephalus microplus*. Vet Parasitol. 2015;210:118–22. https://doi.org/10.1016/j.vetpar.2015.03.010.
113. Soares AMS, Penha TA, de Araújo SA, Cruz EMO, Blank AF, Costa-Junior LM. Assessment of different *Lippia sidoides* genotypes regarding their acaricidal activity against *Rhipicephalus* (*Boophilus*) *microplus*. Rev Bras Parasitol Vet. 2016;25:401–6. https://doi.org/10.1590/S1984-29612016087.
114. Diniz JA, Marchesini P, Zeringóta V, Matos RS, Novato TPL, Melo D, et al. Chemical composition of essential oils of different *Siparuna guianensis* chemotypes and their acaricidal activity against *Rhipicephalus microplus* (Acari: Ixodidae): influence of *α*-bisabolol. Int J Acarol. 2021;48:36-42. https://doi.org/10.1080/01647954.2021.2009910.
115. Safford RJ, Basketter DA, Allenby CF, Goodwin BFJ. Immediate contact reactions to chemicals in the fragrance mix and a study of the quenching action of eugenol. Br J Dermatol. 1990;123:595–606. https://doi.org/10.1111/j.1365-2133.1990.tb01476.x.
116. Miresmailli S, Isman MB. Botanical insecticides inspired by plant-herbivore chemical interactions. Trends Plant Sci. 2014;19:29–35. https://doi.org/10.1016/j.tplants.2013.10.002.
117. Holdsworth PA, Kemp D, Green P, Peter RJ, De Bruin C, Jonsson NN, et al. World Association for the Advancement of Veterinary Parasitology guidelines for evaluating the efficacy of acaricides against ticks (Ixodidae) on ruminants. Vet Parasitol. 2006;136:29–43. https://doi.org/10.1016/j.vetpar.2005.11.011.
118. Holdsworth P, Rehbein S, Jonsson NN, Peter R, Vercruysse J, Fourie J. World Association for the Advancement of Veterinary Parasitology (WAAVP) second edition: guideline for evaluating the efficacy of parasiticides against ectoparasites of ruminants. Vet Parasitol. 2022;302:109613. https://doi.org/10.1016/j.vetpar.2021.109613.
119. Brasil. Portaria nº 48, de 12 de maio de 1997. Brasília: Diário Oficial da União; 1997.
120. Marchiondo AA, Holdsworth PA, Fourie LJ, Rugg D, Hellmann K, Snyder DE, et al. World Association for the Advancement of Veterinary Parasitology second edition: guidelines for evaluating the efficacy of parasiticides for the treatment, prevention and control of flea and tick infestations on dogs and cats. Vet Parasitol. 2013;194:84–97. https://doi.org/10.1016/j.vetpar.2013.02.003.
121. Marchiondo AA, Holdsworth PA, Green P, Blagburn BL, Jacobs DE. World Association for the Advancement of Veterinary Parasitology guidelines for evaluating the efficacy of parasiticides for the treatment, prevention and control of flea and tick infestations on dogs and cats. Vet Parasitol. 2007;143:332–44. https://doi.org/10.1016/j.vetpar.2006.10.028
122. Prescott MJ, Lidster K. Improving quality of science through better animal welfare: the NC3Rs strategy. Lab Anim. 2017;46:152–6. https://doi.org/10.1038/laban.1217.
123. Karlberg AT, Börje A, Duus Johansen J, Lidén C, Rastogi S, Roberts D, et al. Activation of non-sensitizing or low-sensitizing fragrance substances into potent sensitizers - Prehaptens and prohaptens. Contact Derm. 2013;69:323–34. https://doi.org/10.1111/cod.12127.
124. Martins RM, González FHD. Uso del aceite de citronela de Java (*Cymbopogon winterianus* Jowitt) (Panicoidideae) como acaricida frente a

la garrapata *Boophilus microplus* Canestrini (Acari: Ixodidae). Rev Bras Plantas Med. 2007;9:1–8.
125. Boito JP, Santos RC, Vaucher RA, Raffin R, Machado G, Tonin AA, et al. Evaluation of tea tree oil for controlling *Rhipicephalus microplus* in dairy cows. Vet Parasitol. 2016;225:70–2. https://doi.org/10.1016/j.vetpar.2016.05.031.
126. Santos DS, Boito JP, Santos RCV, Quatrin PM, Ourique AF, dos Reis JH, et al. Nanostructured cinnamon oil has the potential to control *Rhipicephalus microplus* ticks on cattle. Exp Appl Acarol. 2017;73:129–38. https://doi.org/10.1007/s10493-017-0171-5.
127. Furlong J. Carrapato: problemas e soluções. Juiz de Fora: Embrapa Gado de Leite; 2005.
128. Prata MC de A, Furlong J, Martins JRS. Carrapato e vermes: inimigos do gado e do produtor.Circ. Técnica 95. Juiz de Fora: Embrapa Gado de Leite; 2008.
129. Andreotti R, Garcia MV, Koller WW. Controle estratégico dos carrapatos nos bovinos. In: Andreotti R, Garcia MV, Koller WW, editors. Carrapatos na cadeia produtiva de bovinos. Brasília, DF: Embrapa; 2019. p. 125–35.
130. Silva EMG, Rodrigues VS, Jorge JO, Osava CF, Szabó MPJ, Garcia MV, et al. Efficacy of *Tagetes minuta* (Asteraceae) essential oil against *Rhipicephalus sanguineus* (Acari: Ixodidae) on infested dogs and *in vitro*. Exp Appl Acarol. 2016;70:483–9. https://doi.org/10.1007/s10493-016-0092-8.
131. Amer AM, Amer MM. Efficacy and safety of natural essential oils mixture on tick infestation in dogs. Adv Anim Vet Sci. 2020;8:398–407. https://doi.org/10.17582/journal.aavs/2020/8.4.398.407
132. John MS, Maske DK, Jayraw AK. Efficacy of herbal essential oils against tick parasitism in goats. J Vet Parasitol. 2009;23:203–4.
133. Kouam MK, Payne VK, Miégoué E, Tendonkeng F, Lemoufouet J, Kana JR, et al. Evaluation of *in vivo* acaricidal effect of soap containing essential oil of *Chenopodium ambrosioides* leaves on *Rhipicephalus lunulatus* in the western highland of Cameroon. J Pathog. 2015. https://doi.org/10.1155/2015/516869.
134. Peebles J, Gwebu E, Oyedeji O, Nanyonga S, Kunene N, Jackson D, et al. Composition and biological potential of essential oil from *Thelechitonia trilobata* growing in South Africa. Nat Prod Commun. 2011;6:1945–8. https://doi.org/10.1177/1934578X1100601238.
135. Mwangi EN, Hassanali A, Essuman S, Myandat E, Moreka L, Kimondo M. Repellent and acaricidal properties of *Ocimum suave* against *Rhipicephalus appendiculatus* ticks. Exp Appl Acarol. 1995;19:11–8. https://doi.org/10.1007/BF00051933.
136. Perez CA. Estudos e estratégias para o controle de carrapatos *Amblyomma*, vetor da Febre maculosa brasileira, no Campus "Luiz de Queiroz" USP/Piracicaba, SP. In: Meira AM de, Cooper M, Ferraz KMPM de B, Monti J de A, Caramez RB, Delitti WBC, editors. Febre maculosa: dinâmica da doença, hospedeiros e vetores. Piracicaba SP: ESALQ; 2013 p. 74–94.
137. Pinter A. Febre maculosa brasileira - vigilância acarológica e controle, in: Meira AM de, Cooper M, Ferraz KMPM de B, Monti J de A, Caramez RB, Delitti WBC, editors. Febre maculosa: dinâmica da doença, hospedeiros e vetores. Piracicaba SP: ESALQ; 2013 p. 63–73.
138. Donalisio MR, Souza CE, Angerami RN, Samy AM. Mapping Brazilian spotted fever: linking etiological agent, vectors, and hosts. Acta Trop. 2020;207:105496. https://doi.org/10.1016/j.actatropica.2020.105496.
139. Stafford KC, Williams SC. Deer-targeted methods: a review of the use of topical acaricides for the control of ticks on white-tailed deer. J Integr Pest Manag. 2017;8:19. https://doi.org/10.1093/jipm/pmx014.
140. Andreotti R, Garcia MV, Cunha RC, Barros JC. Protective action of *Tagetes minuta* (Asteraceae) essential oil in the control of *Rhipicephalus microplus* (Canestrini, 1887) (Acari: Ixodidae) in a cattle pen trial. Vet Parasitol. 2013;197:341–5. https://doi.org/10.1016/j.vetpar.2013.04.045.
141. Agnolin CA, Olivo CJ, Parra CLC, Aguirre PF, Bem CM, Zeni D, et al. Eficácia acaricida do óleo de citronela contra o *Rhipicephalus* (*Boophilus*) *microplus*. Rev Bras Saúde e Prod Anim. 2014;15:604–12. https://doi.org/10.1590/S1519-99402014000300007.
142. Klafke GM, Thomas DB, Miller RJ, Pérez de León AA. Efficacy of a water-based botanical acaricide formulation applied in portable spray box against the southern cattle tick, *Rhipicephalus* (*Boophilus) microplus* (Acari: Ixodidae), infesting cattle. Ticks Tick Borne Dis. 2021;12:101721. https://doi.org/10.1016/j.ttbdis.2021.101721.
143. Ibrahium SM, Aboelhadid SM, Wahba AA, Farghali AA, Miller RJ, Abdel-Baki AAS, et al. Preparation of geranium oil formulations effective for control of phenotypic resistant cattle tick *Rhipicephalus annulatus*. Sci Rep. 2022;12:11693. https://doi.org/10.1038/s41598-022-14661-5.
144. Balashov YS. Bloodsucking ticks (Ixodoidea) - vectors of disease in man and animals, in: Misc Publ Entomol Soc Am. 1972;8:163–376.
145. Hackman RH, Filshie BK. The tick cuticule, in: Obenchain FD, Galun R, editors. Physiology of ticks. 1st ed. Oxford: Pergamon Press; 1982. p. 509. https://doi.org/10.1016/c2013-0-03261-6
146. Jordan RA, Dolan MC, Piesman J, Schulze TL. Suppression of host-seeking *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae) nymphs after dual applications of plant-derived acaricides in New Jersey. J Econ Entomol. 2011;104:659–64. https://doi.org/10.1603/EC10340.
147. Bharadwaj A, Stafford KC, Behle RW. Efficacy and environmental persistence of nootkatone for the control of the blacklegged tick (Acari: Ixodidae) in residential landscapes. J Med Entomol. 2012;49:1035–44. https://doi.org/10.1603/ME11251.
148. Araújo LX, Novato TPL, Zeringota V, Matos RS, Senra TOS, Maturano R, et al. Acaricidal activity of thymol against larvae of *Rhipicephalus microplus* (Acari: Ixodidae) under semi-natural conditions. Parasitol Res. 2015;114:3271–6. https://doi.org/10.1007/s00436-015-4547-3.
149. Schulze TL, Jordan RA. Synthetic pyrethroid, natural product, and entomopathogenic fungal acaricide product formulations for sustained early season suppression of host-seeking *Ixodes scapularis* (Acari: Ixodidae) and *Amblyomma americanum* nymphs. J Med Entomol. 2021;58:814–20. https://doi.org/10.1093/jme/tjaa248.
150. Dolan MC, Jordan RA, Schulze TL, Schulze CJ, Manning MC, Ruffolo D, et al. Ability of two natural products, nootkatone and carvacrol, to suppress *Ixodes scapularis* and *Amblyomma americanum* (Acari: Ixodidae) in a Lyme disease endemic area of New Jersey. J Econ Entomol. 2009;102:2316–24. https://doi.org/10.1603/029.102.0638.
151. Quadros DG, Johnson TL, Whitney TR, Oliver JD, Chávez ASO. Plant-derived natural compounds for tick pest control in livestock and wildlife: Pragmatism or utopia? Insects. 2020;11:490. https://doi.org/10.3390/insects11080490.
152. Vale L, de Paula LGF, Vieira MS, Alves SGA, Moraes Junior NR, Gomes MDF, et al. Binary combinations of thymol, carvacrol and eugenol for *Amblyomma sculptum* control: Evaluation of *in vitro* synergism and effectiveness under semi-field conditions. Ticks Tick Borne Dis. 2021;12:101816. https://doi.org/10.1016/j.ttbdis.2021.101816.
153. SINDAN. Compêndio de produtos veterinários. Sind. Nac. da Indústria Prod. para Saúde Anim. 2022. https://mapa-indicadores.agricultura.gov.br/publico/single/?appid=a3e9ce67-d63b-43ff-a295-20123996ead7&sheet=4c2ec12f-be27-47f2-8136-e2fd18cbb54a&lang=pt-BR&opt=ctxmenu&select=clearall Accessed 9 Mar 2022.
154. Scott IM, Jensen HR, Philogène BJR, Arnason JT. A review of *Piper* spp. (Piperaceae) phytochemistry, insecticidal activity and mode of action. Phytochem Rev. 2008;7:65–75. https://doi.org/10.1007/s11101-006-9058-5.
155. Costa-Júnior LM, Miller RJ, Alves PB, Blank AF, Li AY, Pérez de León AA. Acaricidal efficacies of *Lippia gracilis* essential oil and its phytochemicals against organophosphate-resistant and susceptible strains of *Rhipicephalus (Boophilus) microplus*. Vet Parasitol. 2016;228:60–4. https://doi.org/10.1016/j.vetpar.2016.05.028.
156. Novato TP, Milhomem MN, Marchesini PBC, Coutinho AL, Silva IS, Perinotto WMS, et al. Acaricidal activity of carvacrol and thymol on acaricide-resistant *Rhipicephalus microplus* (Acari: Ixodidae) populations and combination with cypermethrin: Is there cross-resistance and synergism? Vet Parasitol. 2022;310:109787. https://doi.org/10.1016/j.vetpar.2022.109787.
157. Agnolin CA, Olivo CJ, Leal MLR, Beck RCR, Meinerz GR, Parra CLC, et al. Eficácia do óleo de citronela [*Cymbopogon nardus* (L.) Rendle] no controle de ectoparasitas de bovinos. Rev Bras Plantas Med. 2010;12:482–7. https://doi.org/10.1590/s1516-05722010000400012.
158. Valente PP, Moreira GHFA, Serafini MF, Facury-Filho EJ, Carvalho AÚ, Faraco AAG, et al. *In vivo* efficacy of a biotherapic and eugenol formulation against *Rhipicephalus microplus*. Parasitol Res. 2017;116:929–38. https://doi.org/10.1007/s00436-016-5366-x.
159. Olivo CJ, Agnolin CA, Parra CLC, Vogel FSF, Richards NSPS, de Pellegrini LG, et al. Efeito do óleo de eucalipto (*Corymbia citriodora*) no controle do carrapato bovino. Cienc Rural. 2013;43:331–7. https://doi.org/10.1590/S0103-84782013000200023.

160. Nicholson SS. Toxicity of insecticides and skin care products of botanical origin. Vet Dermatol. 1995;6:139–43. https://doi.org/10.1111/j.1365-3164.1995.tb00057.x.
161. Woolf A. Essential oil poisoning. J Toxicol - Clin Toxicol. 1999;37:721–7. https://doi.org/10.1081/CLT-100102450.
162. Allenby CF, Gooowin BFJ, Safford RJ. Diminution of immediate reactions to cinnamic aldehyde by eugenol. Contact Dermat. 1984;11:322–3. https://doi.org/10.1111/j.1600-0536.1984.tb01025.x.
163. Pavela R. Essential oils from *Foeniculum vulgare* Miller as a safe environmental insecticide against the aphid *Myzus persicae* Sulzer. Environ Sci Pollut Res. 2018;25:10904–10. https://doi.org/10.1007/s11356-018-1398-3.
164. Benelli G, Pavela R, Drenaggi E, Desneux N, Maggi F. Phytol, (*E*)-nerolidol and spathulenol from *Stevia rebaudiana* leaf essential oil as effective and eco-friendly botanical insecticides against *Metopolophium dirhodum*. Ind Crops Prod. 2020;155:112844. https://doi.org/10.1016/j.indcrop.2020.112844.
165. Nwanade CF, Wang M, Li H, Masoudi A, Yu Z, Liu J. Individual and synergistic toxicity of cinnamon essential oil constituents against *Haemaphysalis longicornis* (Acari: Ixodidae) and their potential effects on non-target organisms. Ind Crops Prod. 2022;178:114614. https://doi.org/10.1016/j.indcrop.2022.114614.
166. Nwanade CF, Wang M, Wang T, Zhang X, Wang C, Yu Z, et al. Acaricidal activity of *Cinnamomum cassia* (Chinese cinnamon) against the tick *Haemaphysalis longicornis* is linked to its content of (*E*)-cinnamaldehyde. Parasit Vectors. 2021;14:330. https://doi.org/10.1186/s13071-021-04830-2.
167. Elias SP, Lubelczyk CB, Rand PW, Staples JK, Amand TWS, Stubbs CS, et al. Effect of a botanical acaricide on *Ixodes scapularis* (Acari: Ixodidae) and nontarget arthropods. J Med Entomol. 2013;50:126–36. https://doi.org/10.1603/ME12124.
168. Pino-Otín MR, Ballestero D, Navarro E, González-Coloma A, Val J, Mainar AM. Ecotoxicity of a novel biopesticide from *Artemisia absinthium* on non-target aquatic organisms. Chemosphere. 2019;216:131–46. https://doi.org/10.1016/j.chemosphere.2018.09.071.
169. Miura PT, Jonsson CM, de Queiroz SCN, Chagas EC, Chaves FCM, Reyes FGR. Ecological risk assessment of *Piper aduncum* essential oil in non-target organisms. Acta Amaz. 2021;51:71–8. https://doi.org/10.1590/1809-4392202002691.
170. Miura PT, Queiroz SCN, Jonsson CM, Chagas EC, Chaves FCM, Reyes FG. Study of the chemical composition and ecotoxicological evaluation of essential oils in *Daphnia magna* with potential use in aquaculture. Aquac Res. 2021;52:3415–24. https://doi.org/10.1111/are.15186.
171. Jesser E, Yeguerman C, Gili V, Santillan G, Murray AP, Domini C, et al. Optimization and characterization of essential oil nanoemulsions using ultrasound for new ecofriendly insecticides. ACS Sustain Chem Eng. 2020;8:7981–92. https://doi.org/10.1021/acssuschemeng.0c02224.
172. Health for animals. Global trends in the animal health sector. Brussels: Belgium; 2022.
173. Selzer PM, Epe C. Antiparasitics in animal health: quo vadis? Trends Parasitol. 2021;37:77–89. https://doi.org/10.1016/j.pt.2020.09.004.
174. Sneeringer S, Bowman M, Clancy M. The U.S. and EU animal pharmaceutical industries in the age of antibiotic resistance. Washington, D.C; 2019. Report No.: ERR-264.
175. Richter S, Hunte J, Hellmann K. Registration of novel parasiticides under the new 2022 EU regulation. Biol Life Sci Forum. 2021;5:2. https://doi.org/10.3390/blsf2021005002.
176. George DR, Callaghan K, Guy JH, Sparagano OAE. Lack of prolonged activity of lavender essential oils as acaricides against the poultry red mite (*Dermanyssus gallinae*) under laboratory conditions. Res Vet Sci. 2008;85:540–2. https://doi.org/10.1016/j.rvsc.2008.02.001.
177. George DR, Sparagano OAE, Port G, Okello E, Shiel RS, Guy JH. The effect of essential oils showing acaricidal activity against the poultry red mite (*Dermanyssus gallinae*) on aspects of welfare and production of laying hens. Anim Welf. 2010;19:265–73. https://doi.org/10.1017/S0962728600001640.
178. Camilo CJ, Nonato CFA, Galvão-Rodrigues FF, Costa WD, Clemente GG, Macedo MACS, et al. Acaricidal activity of essential oils. Trends Phytochem Res. 2017;1:183–98.
179. Regnault-Roger C, Vincent C, Arnason JT. Essential oils in insect control: low-risk products in a high-stakes world. Annu Rev Entomol. 2012;57:405–24. https://doi.org/10.1146/annurev-ento-120710-100554.
180. Pereira JR, da Silva SMP, Marques MOM. Efficacy of essential oil of *Lippia sidoides* (Verbenaceae) for controlling the cattle tick *Rhipicephalus* (*Boophilus*) *microplus* on naturally parasitized animals under field conditions. Vet Parasitol. 2022;311:109788. https://doi.org/10.1016/j.vetpar.2022.109788.
181. Novato T, Gomes GA, Zeringóta V, Franco CT, de Oliveira DR, Melo D, et al. *In vitro* assessment of the acaricidal activity of carvacrol, thymol, eugenol and their acetylated derivatives on *Rhipicephalus microplus* (Acari: Ixodidae). Vet Parasitol. 2018;260:1–4. https://doi.org/10.1016/j.vetpar.2018.07.009.
182. Tavares CP, Sousa IC, Gomes MN, Miró V, Virkel G, Lifschitz A, et al. Combination of cypermethrin and thymol for control of *Rhipicephalus microplus*: Efficacy evaluation and description of an action mechanism. Ticks Tick Borne Dis. 2022;13:10187. https://doi.org/10.1016/j.ttbdis.2021.101874.
183. Chungsamarnyart N, Jiwajinda S. Acaricidal activity of volatile oil from lemon and citronella grasses on tropical cattle ticks. Nat Sci Suppl. 1992;26:46–51.
184. Agnolin CA, Olivo CJ, Sangioni LA, Parra CLC, Diehl MS, dos Santos JC, et al. Concentrações de óleo de citronela no controle do carrapato de bovinos. Rev Bras Agroecol. 2010;5:187–93.
185. Chagas ACS, Domingues LF, Fantatto RR, Giglioti R, Oliveira MCS, Oliveira DH, et al. *In vitro* and *in vivo* acaricide action of juvenoid analogs produced from the chemical modification of *Cymbopogon* spp. and *Corymbia citriodora* essential oil on the cattle tick *Rhipicephalus* (*Boophilus*) *microplus*. Vet Parasitol. 2014;205:277–84. https://doi.org/10.1016/j.vetpar.2014.06.030.
186. Rand PW, Lacombe EH, Elias SP, Lubelczyk CB, Amand TS, Smith RP. Trial of a minimal-risk botanical compound to control the vector tick of Lyme disease. J Med Entomol. 2010;47:695–8. https://doi.org/10.1603/ME09283.
187. GBIF: The Global Biodiversity Information Facility. 2022. What is GBIF? https://www.gbif.org/what-is-gbif Accessed 12 Sept 2022.
188. Royal Society of Chemistry. The Merck index online. 2022. https://merckindex.rsc.org Accessed 12 Sept 2022.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.