REVIEW PAPER

Plant-Derived Phytochemicals as Sustainable Acaricides: *In Vitro* Screening Strategies, Mechanisms of Action and Developmental Prospects for Veterinary Tick Control

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ABSTRACT

Ticks are among the most important ectoparasites affecting livestock health and productivity, particularly in tropical regions such as India. For decades, synthetic acaricides have been the primary method of control; however, their indiscriminate and prolonged use has led to several drawbacks, including the development of resistant tick populations, environmental contamination and the presence of harmful residues in animal-derived products. In response to these concerns, plant-derived phytochemicals have gained increasing attention as safer and more sustainable alternatives. This review highlights phytochemicals with acaricidal potential, focusing on their screening methods, mechanisms of action and future applicability in veterinary tick management. Evidence indicates that diverse phytochemical groups such as alkaloids, terpenoids, flavonoids, tannins and phenolic compounds demonstrate notable activity against key tick species like Rhipicephalus microplus, Rhipicephalus annulatus, and Hyalomma anatolicum. These compounds exert their effects through multiple pathways, including inhibition of acetylcholinesterase, disruption of octopaminergic signalling, interference with reproduction, suppression of detoxification enzymes, and damage to the tick cuticle. Standard in vitro assays, including larval packet, larval immersion and adult immersion tests, are widely employed to evaluate efficacy. Despite promising findings, practical application remains constrained by challenges such as poor solubility, volatility, instability, and variability in phytochemical composition. Overall, while phytochemicals present a compelling eco-friendly alternative to synthetic acaricides, further advancements in formulation strategies, standardization, and safety assessment are essential to ensure their effective and reliable use in field conditions.

Keywords: Acaricidal activity, Essential oils, Phytochemicals, Plant-derived acaricides, Tick control, Veterinary parasitology

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1. INTRODUCTION

Ticks and mites, belonging to the subclass Acari, are small arthropod ectoparasites that have emerged as a serious menace to the health and productivity of livestock in India, where agricultural practices and animal husbandry are of prime importance for the survival of the rural population[1]. Tick infestations lead to loss of blood, decreased body weight, hide, and udder lesions, as well as decreased milk production, besides acting as vectors for various diseases[2].

Traditionally, before the 1940s, pest management practices relied on the use of aromatic plants. However, with the introduction of synthetic acaricides, tick management practices changed. However, tick resistance to acaricides, environmental pollution, and residue in meat, milk, and other animal products are some of the major concerns[3]. However, Rhipicephalus microplus, R. annulatus, and Hyalomma anatolicum have been found to have widespread distribution and are considered the most economically important ticks infesting Indian cattle[4]. The financial loss due to TTBDs is extremely alarming, as a recent study estimated that the financial loss amounts to 61,076.46 million INR (USD 787.63 million) every year, out of which 46,199.31 million INR (USD 595.07 million) is due to direct productivity loss. In addition, indirect losses due to disease management and mortality are estimated to the tune of 14,877.15 million INR (USD 191.15 million). In India, synthetic acaricides are found to be the most dominant method of controlling ticks, but the use of a single method is not effective as it is challenged by recurring parasite populations[1].

Over the years, various chemical compounds have been used, but resistance to these compounds, whether singular or cross-resistance, has been reported[5]. However, the most important chemical compounds currently being used, namely, organophosphates, fourth-generation synthetic pyrethroids, and amidines, have shown reduced effectiveness, increased costs, and their impact on the environment, as well as the buildup of tolerance in ticks[6].

Limitations of Synthetic Acaricides: Ticks can develop resistance to acaricides within a period of 5-10 years after a new acaricide is introduced. Secondly, the chemicals can persist in the environment, thus affecting other non-target organisms. These chemicals can contaminate water and soil, which can be a threat to the environment. Food safety is another threat associated with acaricides. Residues can be present in milk and meat, which can be a threat to human safety. Secondly, synthetic acaricides can be harmful to non-target organisms. These acaricides can be a threat to people handling them[7].

Natural acaricides: an emerging solution

Natural acaricides refer to bioactive substances that are mostly derived from plant and herbal sources, as well as some microbial sources. They are used as topical formulations, feed additives, sprays, and powders. They have been shown to kill ticks or prevent their feeding, as well as interfere with their reproduction and repellency. Crude extracts from plants have shown significant acaricidal activity, which includes the mortality of adult ticks, feeding inhibition, hatching inhibition, moulting inhibition, fecundity inhibition, and egg viability. Ecological safety and the diversity of the bioactive ingredients of the acaricides minimize the risks of resistance development among tick populations[8]. Advances in formulation techniques have improved the efficacy of eco-friendly acaricidal products, which include essential oils, plant extracts, and allelochemicals[9]. Over 200 plant species found around the world have shown acaricidal or tick-repellent properties. Essential oils have shown significant promise as acaricidal products due to their selective toxicity, biodegradability, and low non-target impact[10].

2. PHYTOCHEMICALS AND THEIR ACARICIDAL ACTIVITY

Phytochemicals are bioactive plant-derived secondary metabolites that are chemically distinct from the primary metabolites which are vital for plant growth and development. Primary metabolites are necessary for basic physiological functions, whereas secondary metabolites play various ecological roles, including protection against pests[11]. Phytochemicals with acaricidal activity are part of several major classes with well-characterized effects on tick physiology: alkaloids (nicotine, atropine, berberine) are neurotoxic and induce paralysis; terpenoids affect cellular membranes and development; phenolics and polyphenols (flavonoids, tannins) affect enzymes and viability. Other significant classes include glycosides, saponins, quinones, fatty acid amides (spilanthol), organosulfur compounds, phenylpropanoids (eugenol), and pyrethrins, which affect membranes, enzymes, oxidative stress, and the nervous system dysfunction[12]. \

3. MECHANISMS OF PHYTOCHEMICAL ACARICIDAL ACTION

3.1. Neurotoxicity Effects:

The three proposed mechanisms of the neurotoxic acaricidal effects of essential oils are: the inhibition of acetylcholinesterase (AChE)[13]. Antagonism of octopamine receptors and GABA receptor. However, the role of GABA in the insecticidal effect of essential oils is a subject of controversy[14]. Some studies indicate the effect of essential oils as the activation of GABA gated chloride channels, whereas other studies indicate the effect of essential oils as the activation of chloride current by GABA[15]. These neurophysiological disorders lead to tick paralysis and death, as shown in Figure.1. (A).

3.2. Inhibition of Acetylcholinesterase:

Acetylcholine (ACh) is a key neurotransmitter in the central and peripheral nervous systems of arthropods Acetylcholinesterase (AChE) regulates ACh activity in arthropods at synapses and neuromuscular junctions by rapidly metabolizing ACh to terminate nerve impulses (Anderson & Coats, 2012). Plant-derived essential oils and terpenoids, such as α-pinene, β-pinene, β-phellandrene, carvacrol, limonene, menthol, menthone, 1,8-cineole (Eucalyptol), linalool, and citral, inhibit AChE[16]. This results in the accumulation of acetylcholine in the synapses due to its inability to be metabolized by AChE. This causes continuous stimulation of nerves, neuromuscular hyperexcitation, and finally tick paralysis. Terpinen-4-ol and carvacrol are potent AChE inhibitors. The former is more potent than thymol due to hydroxyl group positioning[17]. as illustrated in Figure.1(B).

3.3. Binding to Octopamine Receptors:

Octopamine is a multifunctional biogenic amine that plays the role of a neurotransmitter, neurohormone, and neuromodulator in invertebrates. It is analogous to the role of noradrenaline in vertebrates. Together with dopamine, tyramine, serotonin, and histamine, octopamine-tyramine signalling controls important physiological events, including metabolism and behaviour, in arthropods. Essential oil compounds, including eugenol, α-terpineol, and cinnamic alcohol, interact with octopamine and tyramine receptors, acting as agonists. These agonists induce the elevation of intracellular levels of cAMP and Ca^{2+}, leading to the activation of protein kinases A and C, which induce the phosphorylation of ion channels and other proteins, leading to physiological disruption and death in ticks[18]. as shown in Figure.1(C).

3.4. Metabolic Interference Inhibition of Detoxification Systems (CYPs, GSTs, Esterases):

Ticks use detoxification enzymes like cytochrome P450 monooxygenases (CYPs), glutathione S-transferases (GSTs), and esterase to metabolize xenobiotics like acaricides. Various phytochemicals are known to inhibit these detoxification enzymes, which reduces the ticks' ability to detoxify toxic substances. Inhibition of these detoxification mechanisms increases the efficacy of acaricides, both natural and synthetic. Inhibition of these detoxification mechanisms may also result in the bioaccumulation of toxic metabolites, which may eventually lead to the death of ticks[19]. Inhibition of detoxification mechanisms in ticks disrupts the metabolism of xenobiotics, which results in the bioaccumulation of toxic metabolites in ticks, as depicted in Figure.1(D)

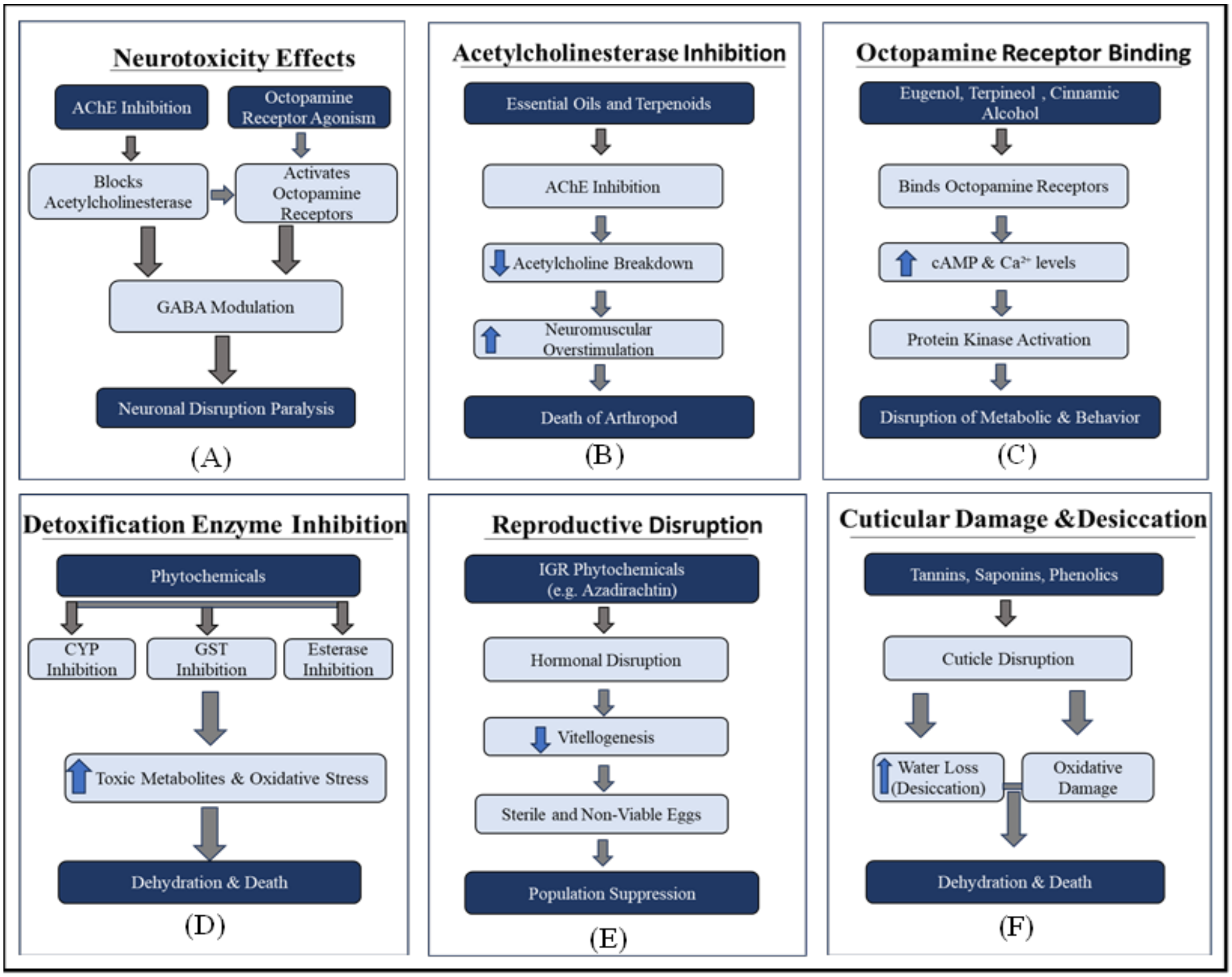
3.5. Reproductive Disruption Growth Regulation and Ovicidal Action:

Some phytochemicals are insect growth regulators (IGRs) that affect the endocrine system, which controls the growth and development of ticks. The best example of an IGR is azadirachtin, found in Azadirachta indica (Neem), which affects the endocrine system, thereby controlling the growth and development of ticks. It affects the ecdysteroid and juvenile hormone system, leading to sterile eggs and changes in mating and oviposition behaviour. It also affects egg viability. These phytochemicals reduce the population development of ticks even if adults are killed in smaller numbers[20]. Hence, interference in the endocrine system affects the reproduction and egg viability of ticks, thereby reducing their population development, as shown in Figure.1(E).

3.6. Cuticular Damage and Desiccation (Tannins, Saponins, Phenolics):

Some phytochemicals affect the integrity of the cuticle in ticks and mites. Tannins and certain saponins can react with cuticular proteins and lipids, causing structural weakening or increased permeability, which can result in increased water loss (desiccation) or the entry of additional toxicants. Quinones, together with oxidizing phenolics, may also cause oxidative damage to the epicuticle[21]. The disruption of the integrity of the cuticle results in increased water loss, causing desiccation, which can eventually kill ticks, as depicted in Figure.1(F).

Figure.1: Mechanisms of phytochemical acaricidal action against ticks.



(A) Neurotoxicity effects; (B) Acetylcholinesterase inhibition; (C) Octopamine receptor binding; (D) Detoxification enzyme inhibition (CYP, GST, esterases); (E) Reproductive disruption; (F) Cuticular damage and desiccation. Abbreviations: AChE, acetylcholinesterase; CYP, cytochrome P450; GST, glutathione S-transferase; cAMP, cyclic adenosine monophosphate.

4. APPROACHES FOR PLANT-DERIVED ACARICIDES

However, the use of plant-derived acaricides in animal production is often dependent on the formulation strategies that ensure the stability, solubility, and acaricidal efficacy of the phytochemicals. For example, many plant secondary metabolites, especially essential oils and terpenoids, are often volatile and have poor water solubility, which may limit their residual activity and acaricidal efficacy. Therefore, the formulation of plant-derived acaricides has been explored to improve their efficacy against ticks.

4.1. Essential-Oil-Based Formulations:

Essential oils of aromatic plants, as botanical acaricides, have been extensively studied for their bioactive compounds, e.g., monoterpenes and phenylpropanoids. These oils are often formulated as sprays, dips, or emulsifiable concentrates for topical application to animals, enhancing the application of hydrophobic compounds and facilitating contact with the tick cuticle. Oils extracted from plants, e.g., Lippia gracilis and Lantana camara, exhibited strong acaricidal activity against Rhipicephalus microplus, mainly attributed to thymol and carvacrol[22].

4.2. Emulsion and Microemulsion Formulations:

Emulsion-based systems are often utilized to enhance the dispersion of plant-derived compounds. An oil-in-water emulsion enables hydrophobic phytochemicals to be uniformly dispersed within an aqueous medium, thus enabling the improvement of their ability to be applied on animal surfaces. Microemulsions, which are comprised of an oil phase, an aqueous phase, a surfactant, and a co-surfactant, are known to produce a thermodynamically stable system that can improve the ability of active ingredients to penetrate the tick cuticle. Experimental investigations revealed that the use of microemulsions of essential oils can improve repellency and acaricidal activity when compared to crude oil[23].

4.3. Nano formulations:

Recent advances in nanotechnology have led to the development of nano-based phytochemical delivery systems, such as nano emulsions, solid lipid nanoparticles, and nanostructured lipid carriers. These nano-based phytochemical delivery systems enhance the bioavailability and stability of phytochemicals and prevent their degradation in the environment. Furthermore, the controlled and sustained release of active components by nano carriers could extend the duration of acaricidal activity. Scientific studies have proven that nanoencapsulation of essential oils from plants can greatly enhance their acaricidal efficacy against ticks such as Rhipicephalus microplus, highlighting the potential of nanotechnology in botanical tick control strategies[24].

4.4. Encapsulation and Controlled-Release Systems:

Encapsulation technology has also been considered for the improvement of stability and controlled release of plant-based acaricides. In this method, phytochemicals are trapped within a matrix of polymers, liposomes, or cyclodextrin complexes that protect the active ingredients from degradation by environmental factors such as oxidation, photolysis, and volatilization. The method can also be used to regulate the rate of release of active ingredients, thus prolonging the acaricidal activity and minimizing the need for reapplication[25].

4.5. Polyherbal and Combination Formulations:

Another emerging acaricidal approach includes the use of polyherbal formulations, whereby the essential oils of various plant species are blended. This could lead to synergism between the different phytoconstituents, thus enhancing their acaricidal properties. This notion is supported by the acaricidal activity of a polyherbal aqueous formulation, which was assessed using the adult immersion and larval packet tests for R. microplus. This indicates the potential of multi-constituent plant products as eco-friendly acaricides[26].

5. FORMULATION CHALLENGES

Development of phytochemical-based tick control products involves multi-dimensional challenges that affect their stability, efficacy, and marketability in veterinary medicine, as reviewed in the literature. The challenges are related to the physicochemical properties of phytochemicals, such as essential oils and terpenoids, which are quite distinct in their manipulation, application, and performance in comparison to conventional chemical acaracides[27].

5.1. Volatility and Limited Persistence:

Volatile phytochemicals such as monoterpenes and sesquiterpenes in essential oils are highly volatile in nature, thus limiting their residual activity to only 24 to 48 hours. This is less than the required 14 to 28 days to interfere with tick life cycles. GC-MS studies indicate that there is a loss of more than 50 percent in a day at temperatures above 30°C, a common condition in tropical regions. This requires repeated applications of these formulations, thus affecting farmer compliance. Environmental factors such as wind, humidity, and cattle movement also increase the rate of volatilization. Near total depletion has also been observed in field studies after 3 days[27].

5.2. Chemical Degradation Pathways:

The exposure of these phytoconstituents to oxygen, light, and heat causes oxidative polymerization and photo-degradation of the unsaturated phytoconstituents, converting the active ingredients into inactive compounds. Accelerated stability studies using conditions as specified by the ICH guidelines showed a reduction of 60 to 80% potency over 3 months, as the peroxide values increased beyond the desired range due to autoxidation of the allyl groups present in the terpenoid compounds. This effect is more pronounced during storage or exposure to UV light, as the phytoconstituents are subjected to conditions of sunlight exposure to animal hides, as proved by spectroscopic studies of the degraded samples. Instability of the phytoconstituents to heat also adds to the problem, as the temperature of 40°C or more during the preparation of the formulations causes isomerization and hydrolysis, reducing the acaricidal potency as measured by the larval packet test[28].

5.3. Solubility and Dispersion Difficulties:

The largely lipophilic nature of phytochemicals, as indicated by high octanol/water partition coefficients, makes homogeneous incorporation in a variety of carrier systems impossible. This incompatibility is evidenced by poor wetting characteristics and aggregation in a semi-solid or liquid vehicle base, as indicated by centrifugation experiments in which separations greater than 20% volume are observed after 7 days. This results in suboptimal delivery of the active to target tick sensory structures because of uneven distribution that does not reach threshold concentrations for contact toxicity. The choice of solvent also presents problems because polar systems increase solubility but cause leaching, whereas non-polar systems restrict release, as indicated by dissolution profile studies in which less than 30% elution is observed after 24 hours[29].

5.4. Variability in Composition and Potency:

Interspecific as well as intraspecific variations among plants based on genotype, edaphoclimatic conditions, and post-harvest handling result in formulations with variable levels of marker compounds, which may vary as much as 30-70%. Quantitative HPLC analysis has established that this variation is directly related to the fluctuating LC50 values of the formulations, as the coefficient of variation exceeds 40%. Inconsistencies in the formulation may be traced to the differential expression of the biosynthetic pathway, which is compounded by the ineffectiveness of the extraction process that co-extracts inert ballast materials. Poly-phytochemical synergies add to the unpredictability of the formulation, as antagonistic interactions may halve the mortality values in mixture potency studies[30].

5.5. Penetration and Bioavailability Constraints:

Phytochemicals face difficulties in passing through the lipophilic tick cuticle and dermal layers of the host, and dermal retention of phytochemicals is below 20% using ex vivo permeation assays on bovine skin. Interferents present in the host, such as sebum, perspiration, and grooming activities, reduce the concentrations of the phytochemicals, and the rapid metabolic breakdown of phytochemicals by enzymes in the tick's midgut limits the effectiveness of the compounds systemically. Pharmacokinetic studies using radiolabeled compounds to track the compounds' movement confirm that the peak concentrations of bioactive phytochemicals present in the tick's haemolymph rarely reach 10% of the initial dose. These concentrations are inadequate to overcome the metabolic detoxification pathways of the resistant tick strains. Formulation adjuvants designed to improve the permeation of the phytochemicals induce subacute dermal responses, with histopathology revealing epidermal hyperplasia at concentrations above 5%[31].

5.6. Standardization and Quality Control Gaps:

The unavailability of validated monographs on the pharmacopoeia for phytochemical actives creates difficulties in reproducibility, as chemo-profiling by NMR or MS cannot detect minor constituents that add to the activity. This problem manifests as batch release failures due to 25-50% potency variations detected by bioassays due to unquantified adulterants or degradation products. The emphasis on single-entity purity profiling by regulators creates a problem for multi-entity profiling, delaying dossier submissions. Scaling up from the lab to industrial quantities creates further problems, with 2–3-fold yield losses observed in pilot plant operations due to inefficient recovery of solvents and thermal degradation during drying[32].

5.7. Regulatory and Commercialization Impediments:

Phytochemical formulations bypass streamlined clearance due to inadequate toxicological dossiers, including multi-generation reproductive tests and residue depletion kinetics in edible tissues. Maximum residue limit establishment is also lacking, with milk withdrawal periods uncharacterized for most active ingredients, which are major issues in dairy-dependent countries. Economic considerations have also been emphasized, with production costs 2 to 4 times higher than those of synthetics due to fluctuations in raw material availability and long periods required for validation. Deficiencies in field validations also hinder phytochemical entry to the market, with small plot efficacy not correlated with large-scale efficacy in the field, with <60% tick reductions due to IPM attributed to environmental factors[33].

6. IN VITRO METHODS FOR EVALUATING TICK REPELLENCY AND ACARICIDAL ACTIVITY

Ticks are significant veterinary and medical ectoparasites of considerable economic importance and disease-transmitting agents. Resistance to synthetic acaricides has sparked interest in phytochemicals. In vitro tests play a crucial role as a preliminary step for phytochemical screening. Repellency tests measure the behavioural response of the tick, whereas acaricidal tests measure the mortality, neuromuscular effects, and reproductive effects of the phytochemicals. These tests offer standardized results, yielding reliable and quantitative data for the initial identification and evaluation of phytochemicals for tick control[34].

6.1. Petri Dish Bioassay:

Petri dish bioassays have been extensively used for the preliminary evaluation of the repellent activity of phytochemicals for ticks. In these experiments, treated and untreated areas are created within a confined arena, and the ticks are allowed to move freely between the treated and untreated areas. Repellency of the phytochemicals to the ticks is measured by the movement of the ticks between the treated and untreated areas. If the ticks move less to the treated areas, or if they take longer to move to the treated areas, then the phytochemicals are said to exhibit repellent activity. Other types of Petri dish bioassays include the boundary-crossing assay and the two-choice assay, by which the repellent activity of different compounds or formulations can be compared. These assays have been used to compare the repellent activity of plant-based repellents and synthetic repellents, such as DEET[35].

6.2. Tick Climbing Repellency Bioassay:

Tick climbing assays take advantage of the natural questing behaviour of ticks, in which ticks ascend vegetation in search of a host. In this assay, ticks are offered vertical surfaces that have treated and untreated sections. Tick repellent activity is determined by observing the behaviour of ticks, in which repellent activity is based on the decreased ability of ticks to ascend treated surfaces or the avoidance of treated sections when moving upwards. Detachment and falling from treated surfaces are also included as behaviour that can demonstrate repellent activity. Tick climbing assays are advantageous in that they display the behaviour of ticks in a manner that is similar to the real world[36].

6.3. Moving Object Bioassay:

The moving object bioassay is an assay that aims to mimic the interaction between ticks and their moving hosts in a controlled laboratory setting. In the moving object bioassay, ticks are subjected to a heated and moving object that mimics the temperature of their hosts. The assay is an effective tool in the simultaneous evaluation of the spatial repellency and contact repellency of test compounds. The assay is particularly effective in the evaluation of the effects of volatile and semi-volatile phytochemicals on the behaviour of ticks[37].

6.4. Olfactometer Bioassay:

Olfactometer assays are often utilized to study the response of ticks to chemical cues in the air. Olfactometer assays often include a Y-shaped apparatus that permits ticks to make choices between two air channels, each containing the test compound or the control stimulus. Repellency can be assessed by measuring the response of ticks to the odour stimulus. Olfactometer assays are very important in providing valuable information about the involvement of volatile phytochemicals in host-seeking activity[38].

6.5. Larval Packet Test:

The larval packet test is one of the most common tests used to evaluate the acaricidal activity and to detect resistance to acaricides. In this test, tick larvae are exposed to acaricidal-treated surfaces with known concentrations of test substances. The toxic potential of the tested substances is measured by assessing the mortality of tick larvae after a given time. This test is often used to evaluate the efficacy of plant-derived substances on economically important tick species such as Rhipicephalus (Boophilus) microplus[39].

6.6. Larval Tarsal Test:

The larval tarsal test for acaricidal activity is done by exposing newly hatched tick larvae to test compounds in wells of a microplate. The larvae come into contact with the treated surface through their tarsi. The mortality rates obtained after incubation give information about the toxic potential of the tested compounds[40].

6.7. Larval Immersion Test:

Larval immersion test is one of the tests that is often used to assess the toxicity of acaricidal compounds to early stages of tick development. In this test, the test solutions containing the acaricidal compounds are immersed into the larval population, and the mortality is then observed after incubation. This test is often used to screen large numbers of compounds, and it has been used extensively in studies that focus on the acaricidal properties of plant-derived compounds[41].

6.8. Adult Immersion Test:

The adult immersion test is often used to test the effectiveness of acaricidal compounds on adult ticks, especially the engorged females. This test, besides mortality, also includes sublethal effects, i.e., oviposition inhibition, reduction of egg mass, and hatchability of eggs. These reproductive aspects of the ticks give valuable insights into the effects of the compounds to be tested on the population dynamics of the ticks. Phytochemical-rich plant extracts have been extensively studied for their acaricidal properties against different tick species. Plant extracts vary in their acaricidal activity depending on the tick species, the plant extracts, and the bioassay technique. Phytochemicals, i.e., alkaloids, flavonoids, saponins, tannins, terpenoids, and phenolic compounds, have shown significant roles in the acaricidal properties of the plant extracts42. Mortality rates, LC50/LC90, and OI of the selected plant extracts are presented in Table 1.

Table 1: Various plant extract and their mortality rate

Plants	**Target tick species**	**Main phytochemicals/compounds**	***In vitro* type of bioassay**	**Efficacy results (mortality, LC50/LC90, etc.)**
***Cupressus sempervirens* (Mediterranean cypress)[42]**	*Rhipicephalus annulatus*	Eicosapentaenoic acid, Docosadiynedioic acid, flavonoids, tannins, carbohydrates	Spray-Dip Bioassay	100% mortality (14d), LC50 12.2%, LC95 17% at 14d; high efficacy compared to methanol, water, chloroform extracts
***Capsicum frutescens* (Chili)[43]**	*R. (Boophilus) microplus*	Cis-13-octadecenoic acid, n-hexadecanoic acid, flavonoids, tannins, saponins	AIT	LC50 617.54 ppm, LC90 1040.41 ppm, up to 84.35% IR at 650 ppm; methanol > hexane > petroleum ether effectiveness
***Nicotiana tabacum* (Tobacco)[44]**	*R. sanguineus*	Nicotine, citronellal propionate, terpenoids, alkaloids, flavonoids, tannins	AIT, LPT	Hexane higher than methanol; max mortality 99.3% (larvae, 0.07 mg/ml); moderate adult mortality and reproductive inhibition

***Artocarpus lakoocha* (Monkey jack/ Lakoocha)**[45]	*R. (Boophilus) microplus*	Phenolics, tannins	AIT	72% mortality at 1600 µg/ml (48h); LC50 1050 µg/ml; 49% inhibition of egg laying at 1600 µg/ml
Aloe arborescens[46]	*R. (Boophilus) microplus*	Water-soluble tannins, anthraquinones, aloeresin, aloenin, aloin, flavonoids	AIT	Up to 66%-75% OI reduction, 86% PE; highest activity seen for water-soluble tannin-rich solvents
Calpurnia aurea, Otostegia integrifolia[47]	*Amblyomma variegatum*	Alkaloids (C. aurea), saponins, tannins, flavonoids, glycosides, steroids	AIT	C. aurea: 52% mortality at 200 mg/ml (24h); O. integrifolia: 27% mortality; activity dose and time-dependent
Randia aculeata, Moringa oleifera, Carica papaya[48]	*R. (Boophilus) microplus*	Tannins, alkaloids, flavonoids, glucosinolates, phenolic acids	AIT, LPT	R. aculeata seed hydroethanolic: 100% larval, 85% adult mortality (100 mg/ml); C. papaya 75.5% larval, 55% adult

Datura metel, Argemone mexicana[4]	*R. (Boophilus) microplus*	D. metel: alkaloids, glycosides; A. mexicana: alkaloids, terp, flavonoids, phenolics	AIT, LPT	D. metel LC90 7.13%, A. mexicana LC90 11.3%, up to 100% tick mortality (D. metel at 9–10% conc.)
Phytolacca dodecandra[49]	*Rhipicephalus appendiculatus*	Saponins, steroids, flavonoids, terpenoids	Contact Larval Bioassay	LC50 17.3 mg/ml, LC90 26.8 mg/ml (larvae 48h); No cytotoxicity on vero cells
***Azadirachta indica* (Neem)**[50]	*R. microplus*	Hexadecanoic acid, octadecatrienoic acid, lignans, terpenes, carboxylic acids, amides	AIT, LPT	Adult mortality up to 86.7% at 100 mg/ml; LC50 29.21 mg/ml; larval mortality 75.7%
Datura stramonium[51]	*R. microplus*	Hexadecanoic acid, methyl ester, linolenic acid, benzofuranone, flavonoids, alkaloids	AIT, LPT	At 100 mg/ml: 66.67% adult mortality, 70.63% inhibition of oviposition, 65% larval mortality, LC50 61.66 mg/ml

AIT: Adult Immersion Test; LPT: Larval Packet Test; IR: Inhibition rate; OI: Oviposition inhibition; PE: Percent efficacy; LC_{50}/LC_{90}/LC_{95}: concentrations killing 50%, 90%, and 95% of ticks. Units: ppm, parts per million; mg/ml, milligrams per millilitre; µg/ml, micrograms per millilitre.

7. DISCUSSION

Plant-derived phytochemicals show promising acaricidal and repellent activity against several tick species, suggesting potential as eco-friendly alternatives to synthetic acaricides. Bioactive compounds such as alkaloids, terpenoids, flavonoids, and phenolics act through mechanisms including neurotoxicity, enzyme inhibition, and disruption of tick physiology. However, reported efficacy varies due to differences in plant species, extraction methods, and bioassay techniques. Most studies focus on in vitro screening, with limited field validation. Additionally, standardized extraction procedures, phytochemical characterization, and formulation strategies remain insufficient.

8. CONCLUSION

Plant-derived phytochemicals represent promising alternatives to synthetic acaricides for tick control. Bioactive compounds such as terpenoids, alkaloids, flavonoids, and phenolics exhibit acaricidal activity through mechanisms including neurotoxicity, detoxification enzyme inhibition, reproductive disruption, and cuticular damage. Standardized in vitro bioassays remain essential for preliminary evaluation. Advances in formulation strategies, particularly nano-based delivery systems and encapsulation, have improved the stability and efficacy of botanical acaricides. However, further studies on field validation, toxicity assessment, and formulation optimization are required to support their practical application in integrated tick management.

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