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Botanical Acaricides for Sustainable Management of Two-Spotted Spider Mite (*Tetranychus urticae* Koch) in Okra: Current Status and Future Perspectives

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Abstract— *The two-spotted spider mite,* Tetranychus urticae *Koch, has become an important constraint in okra cultivation due to its ability to multiply rapidly and cause serious damage to foliage. Infestation often results in reduced photosynthetic activity, poor plant vigour, and significant losses in yield and marketable quality, particularly under warm and dry conditions. Continuous reliance on synthetic acaricides has resulted in several challenges, including resistance development, pesticide residues, resurgence of pest populations, and adverse effects on beneficial organisms. These concerns have encouraged researchers to explore environmentally safer alternatives for mite management.*

This review critically examines published information on plant-derived acaricides and their potential role in managing T. urticae in okra-based production systems. Findings from studies conducted in India and other countries indicate that neem-based products, garlic-chilli extracts, karanja oil, tulsi extracts, and several essential oils possess significant acaricidal, repellent, and growth-regulating properties. Evidence generated from field investigations conducted under the doctoral research programme of Singh at Banaras Hindu University, Varanasi, indicated that NSKE 5%, azadirachtin 0.03%, and neem oil were among the most promising botanical options for suppressing Tetranychus urticae *populations under field conditions. Unlike many conventional acaricides that primarily target a single physiological pathway, botanical products influence mite populations through several complementary mechanisms, including direct toxicity, feeding inhibition, reproductive suppression, interference with growth and development, reduction in fecundity, and oviposition deterrence. Their comparatively lower toxicity to natural enemies enhances their suitability for incorporation into integrated pest management programmes. Although several promising results have been reported, challenges related to formulation standardisation, field persistence, and large-scale adoption still need to be addressed. Future efforts should focus on improving formulation technology, validating performance across diverse agro-climatic conditions, and promoting farmer awareness. Overall, botanical acaricides offer a promising component of sustainable and residue-conscious mite management strategies in okra cultivation.*

Keywords— Tetranychus urticae Koch, botanical acaricides, neem-based pesticides, integrated pest management, okra, two-spotted spider mite, azadirachtin, NSKE, biopesticides, Abelmoschus esculentus.

I. INTRODUCTION

Okra (*Abelmoschus esculentus* L. Moench) is widely cultivated across tropical and subtropical regions and serves as an important vegetable crop for both nutritional security and farm income generation. India occupies a leading position in global okra production, and the crop contributes significantly to nutritional security and farm income. Despite its economic importance, okra productivity is often constrained by a range of insect and mite pests that reduce both yield and market quality.

Among the arthropod pests associated with okra, the two-spotted spider mite, *Tetranychus urticae* Koch, is increasingly recognized as a key production constraint in several agro-climatic regions. The mite is highly polyphagous and capable of infesting a large number of cultivated and wild host plants. Feeding by mites causes chlorotic speckling, leaf bronzing, premature leaf drop, and reduction in photosynthetic activity. Under severe infestation, substantial yield losses have been reported in susceptible cultivars.

Management of *T. urticae* has traditionally depended on synthetic acaricides because of their rapid action and immediate suppression of mite populations. However, repeated use of these chemicals has resulted in resistance development, residue accumulation, destruction of natural enemies, and occasional pest resurgence. Increasing concerns regarding environmental safety and sustainable crop protection have therefore encouraged the search for alternative management approaches.

Growing concerns regarding pesticide resistance and environmental safety have renewed interest in botanically derived pest-management products as viable alternatives or complementary tools to conventional acaricides. Plant-derived products contain diverse bioactive compounds that can affect mites through multiple physiological and behavioural mechanisms. Their biodegradable nature and relative safety to beneficial organisms make them attractive candidates for integration into IPM programmes. The present review aims to summarise current knowledge on botanical acaricides used against *T. urticae*, discuss their modes of action and field performance, and identify future research priorities for sustainable mite management in okra.

In recent years, increasing concerns regarding pesticide residues, resistance development, environmental contamination, and consumer demand for safer food products have accelerated global interest in botanical pesticides and bio-rational pest management approaches. Botanical acaricides are therefore gaining renewed attention as sustainable alternatives for managing spider mite infestations in vegetable crops.

II. TAXONOMY, BIOLOGY AND LIFE CYCLE

T. urticae Koch, 1836 belongs to Arachnida: Trombidiformes: Tetranychidae. The species is identified by its characteristic pair of dark lateral spots on the abdomen of adult females. Molecular COI barcoding now provides reliable species-level identification across geographically diverse populations (Navajas et al., 2013). In India, both *T. urticae* and the closely related *T. neocaledonicus* Andre have been reported infesting okra. Documented differential infestation by *T. neocaledonicus* across seven okra lines/cultivars at R.A.U. Pusa, with Arka Anamika and D-1-87-5 showing the least susceptibility.

The life cycle consists of egg, larva, protonymph, deutonymph, and adult, completing in 7–14 days at 25–30°C and 40–60% RH. On susceptible okra entry Mahyco 10, the total immature development period was only 10 days, compared to 19.8 days on the resistant Kasturi bhendi. Fecundity on susceptible hosts reached 77.1 eggs/female versus 41.5 eggs/female on resistant entries. The doctoral research of Singh (2017) further demonstrated that among 16 okra varieties screened (2013–2015), Kashi Lalima recorded the lowest mean mite population (56.89 per leaf area), while Varsha Uphar recorded the highest (89.90), and trichome density showed a significant negative correlation (r = –0.71) with mite population.

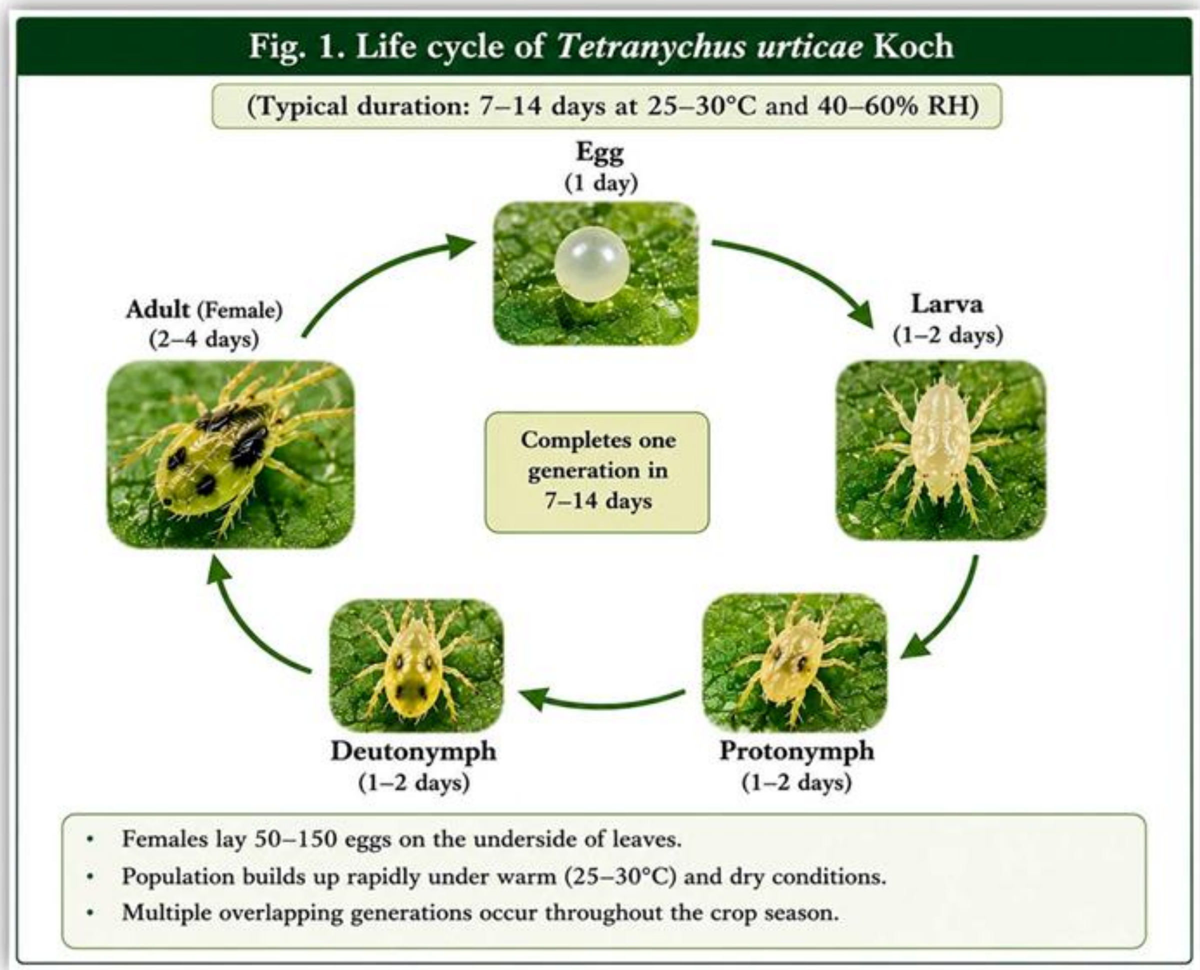

FIGURE 1: Life cycle of *Tetranychus urticae* Koch showing egg, larva, protonymph, deutonymph, and adult stages. The life cycle is completed in 7–14 days at 25–30°C and 40–60% RH.

III. DISTRIBUTION, HOST RANGE AND ECONOMIC DAMAGE

The two-spotted spider mite is among the most widely distributed mite pests in the world and has been reported from nearly all major agricultural regions, except Antarctica. Minhajul-Haque et al. (2011) recorded it on 20 vegetable and 24 ornamental plant species in Rajshahi, Bangladesh, including okra, cucumber, brinjal, tomato, and cowpea, with peak populations in August correlating directly with rising temperatures. Hoque et al. (2010) documented the highest *T. urticae* populations on lady's finger (174.35 per leaf) in August, compared to bean and eggplant, in Bangladesh.

Feeding injury results from the mite puncturing leaf tissues and extracting cellular contents, leading to progressive deterioration of leaf health and physiological activity. Park and Lee (2002) quantified that at 1,000 mite-days per 6 cm² leaf area, net photosynthesis was reduced by ~50–95% and total chlorophyll by ~55–80%. Findings from the doctoral investigations of Singh at Banaras Hindu University indicated that spider mite infestation significantly altered the biochemical composition of okra leaves, resulting in reductions in nitrogen, phosphorus, potassium, and micronutrient contents across susceptible genotypes. In Panjab-7, phosphorus loss of 0.23% in Punjab Padmini, potassium loss up to 0.72% in Azad Bhindi-2, and zinc content decrease of 39.51% in Azad Bhindi-1, among the 16 varieties evaluated. Documented yield losses of 7–48 percent in okra make *T. urticae* one of the most yield-limiting biotic stresses in warm-season okra cultivation.

TABLE 1
SELECTED HOST PLANTS OF *TETRANYCHUS URTICAE* KOCH

Host (Common Name)	Scientific Name	Reference
Okra / Lady's finger	*Abelmoschus esculentus*	Kumar et al. (2014); Geroh (2007)
Brinjal / Eggplant	*Solanum melongena*	Abou-Zaid et al. (2012); Siddiqui & Singh (2006)
Cucumber	*Cucumis sativus*	Park & Lee (2002); El-Adawy & El-Esnawy (2005)
Bean	*Phaseolus vulgaris*	Hoque et al. (2010); Gatarayiha et al. (2012)
Tomato	*Solanum lycopersicum*	Knapp et al. (2003); Makundi & Kashenge (2002)
Rose	*Rosa* spp.	Kumar & Shelke (2009); Singh et al. (2006)
Cotton	*Gossypium hirsutum*	Muhammad et al. (2012)
Strawberry	*Fragaria × ananassa*	Serce & Hancock (2002); Bernardi et al. (2013)
Grapevine	*Vitis vinifera*	Sivritepe et al. (2009)
Cowpea, Spinach	*Vigna unguiculata*, *Spinacia oleracea*	Minhajul-Haque et al. (2011)

IV. ECOLOGY AND POPULATION DYNAMICS

Abiotic factors exercise a decisive influence on *T. urticae* population dynamics. Kumar et al. (2014) monitored populations on okra at Varanasi during 2010–2011 and found peak populations at the 21st standard week (47.75 mites/2.5 cm^2 leaf) in 2010 and the 18th standard week (45.99) in 2011. Mean temperature and sunshine hours were positively correlated, while relative humidity and rainfall showed negative correlation with mite density. Geroh and Gulati (2007) documented bimodal population peaks on okra at Hisar during June (25.69 mites/cm^2 leaf) and August (22.50 mites/cm^2 leaf) in summer–Kharif 2006–07, with *T. urticae* positively correlated with temperature ($r = 0.60–0.78$) and negatively with humidity ($r = –0.39$).

Rising global temperatures driven by climate change are expected to accelerate mite development cycles, expand geographic ranges, and intensify outbreak frequency. Prolonged dry spells increasingly common in the Indo-Gangetic Plain create conditions particularly favourable for rapid population buildup, compounding the urgency of developing climate-resilient botanical acaricide-based IPM strategies.

V. SYNTHETIC ACARICIDES: EFFICACY AND LIMITATIONS

Synthetic acaricides have delivered effective short-term suppression of *T. urticae*. Rai and Singh (2008) recorded dicofol (92.55%), abamectin (88.44%), propargite (82.66%), and ethion (72.44%) as top performers on okra at Varanasi. Field investigations conducted during the doctoral research of Singh at Banaras Hindu University demonstrated that clofentazine and cyflumetofen were among the most effective acaricides against *T. urticae* under field conditions. However, these gains come at substantial ecological and toxicological costs.

Resistance development is the foremost concern: Kim et al. (1995) found 23-fold dicofol resistance in *T. urticae* maintained for one year without selection pressure. Sokeli et al. (2007) reported resistance ratios of 2.3–40.2-fold for chlorpyrifos in Turkish apple orchard populations. Resurgence is a related problem: Kumar and Singh (2002) confirmed that phosphamidon, fluvalinate, fenvalerate, dimethoate, and monocrotophos caused resurgence of spider mites on okra at BHU, whereas Clofentazine (–21.34%), Cyflumetofen (–15.94%), Fenpyroximate (–10.01%) and Propargite (–5.46%) did not induce resurgence in the doctoral investigations of Singh (2017). Singh and Singh (2005) demonstrated at Varanasi that dicofol and monocrotophos caused maximum mortality to the predatory mite *Amblyseius longispinosus*, whereas azadirachtin and sulfur recorded minimum predatory mite mortality, confirming differential selectivity.

VI. BOTANICAL ACARICIDES: CONCEPT AND MAJOR SOURCES

Botanical acaricides are plant-derived preparations comprising crude extracts, essential oils, or purified phytochemicals with acaricidal, repellent, antifeedant, growth-disruptive, or oviposition-deterrent properties. Ignacimuthu et al. (2008) emphasised that they are environment-friendly, economical, target-specific, and easily biodegradable. Ashok et al. (2010) noted that attention has shifted globally toward plant products as 'green pesticides' owing to their non-phytotoxicity, systemicity, easy biodegradability, and stimulatory potential for host plant metabolism. Several plant families, particularly Meliaceae, Fabaceae, Asteraceae, and Lamiaceae, are rich sources of acaricidally active secondary metabolites including terpenoids, alkaloids, phenolics, and volatile oils.

6.1 *Azadirachta indica* (Neem)

Neem remains the most researched and deployed botanical acaricide. Its primary active compound azadirachtin interferes with ecdysone-mediated moulting, inhibits feeding, and deters oviposition. Mironova and Khorkhordin (1997) confirmed that NeemAzal T/S at 0.5% caused 100% adult and nymph mortality of *T. urticae* on fig leaves, and all concentrations (0.1, 0.3, 0.5%) significantly reduced reproductive capacity. Knapp and Kashenge (2003) found that Neemroc EC achieved 78.3% adult mortality with an LC50 of 12.9 ml/l on tomato leaf discs, and all neem formulations caused repellence and oviposition deterrence. Mani et al. (2003) reported that 1,500 ppm azadirachtin caused 50% TSM mortality on okra (cv. Arka Anamika) at Varanasi, while neem oil and NSKE caused up to 30% mortality. The BHU multi-year field results (Singh, 2017) are the most comprehensive Indian okra data available: NSKE 5% achieved 50.84%, azadirachtin 0.03% achieved 49.53%, and neem oil 0.03% achieved 44.60% pooled reduction across two crop seasons. Martinez-Villar et al. (2005) demonstrated sublethal effects at 80 ppm—50% reduction in survival to adulthood and an almost eightfold reduction in fecundity.

6.2 *Pongamia pinnata* (Karanja)

Karanja oil from *Pongamia pinnata* (syn. *Millettia pinnata*) contains karanjin and pongamol as principal acaricidal furanoflavonoids. Mani et al. (2003) evaluated pungum (*Pongamia*) oil at recommended dose against TSM on okra at Varanasi, recording up to 30% mortality—comparable to neem oil. Kumar et al. (2002) observed some mite resurgence following pungum oil application on okra at BHU, suggesting the need for tank mixtures with complementary agents.

6.3 Garlic, Chilli, and Indigenous Organic Preparations

Chandrashekharaiah et al. (2011) evaluated six indigenous products used by organic farmers in Southern Karnataka against *T. urticae* in laboratory bioassays. Chilli plus garlic extract at 10% concentration produced the highest acaricidal activity of all indigenous materials tested—93.91% larval and 65.60% adult mortality—exceeding even the neem seed kernel plus *Calotropis* plus *Aloe vera* combination (87.23% larval, 71.70% adult). Cow urine at 10% caused 43.50% adult mortality, while all materials showed very low ovicidal activity. These results validate the traditional use of garlic-chilli preparations in organic okra cultivation.

6.4 *Ocimum tenuiflorum* (Tulsi)

Kumar et al. (2009) incorporated *O. tenuiflorum* leaf extract (10% aqueous) as a foliar spray in combination with FYM and entomopathogenic fungi on aubergine in Tamil Nadu. FYM at 25 t/ha + *O. tenuiflorum* at 10% achieved 71.66% mite reduction and 63.40% egg reduction over untreated control, with a cost-benefit ratio of 1:3.07 demonstrating economic viability for smallholder organic production systems.

6.5 Plant Extract Screening Studies

Yanar et al. (2011) evaluated crude methanol extracts of 12 plant species against *T. urticae* in controlled bioassays and found that *Lolium perenne* (flower/leaf), *Anthemis vulgaris* (flower), and *Chenopodium album* (flower/leaf) extracts exhibited significantly higher mortality than azadirachtin (10 g/L) and synthetic pesticides at 5% concentration. Ahn et al. (2008) screened 39 aquatic plant extracts and reported *Trapa japonica*, *Rotala* sp., and *Astragalus sinicus* caused 80–97% mortality of *T. urticae*. Dimetry et al. (1993) confirmed that neem seed kernel extracts showed biological activity against *T. urticae*, with pentane extraction producing more potent preparations than aqueous or cold-pressed oil extracts (Sanguanpong & Schmutterer, 1992). Abo-El-Ghar et al. (1986) were among the early workers to screen plant extracts against *T. urticae* in Egypt, reporting significant toxicity of several botanical extracts.

TABLE 2
MAJOR BOTANICAL ACARICIDES EVALUATED AGAINST *TETRANYCHUS URTICAE* KOCH ON OKRA

Botanical Source	Active Compound(s)	Dose / Conc.	Efficacy (%)	Reference
A. indica – NSKE	Azadirachtin, Nimbin	5% (field)	50.84 (mite reduction)	Singh (2017)
A. indica – Azadirachtin	Azadirachtin	0.03% (field)	49.53 (mite reduction)	Singh (2017)
A. indica – Neem oil	Azadirachtin, oils	0.03% (field)	44.60 (mite reduction)	Singh (2017)
NeemAzal T/S	Azadirachtin	0.50%	100% adult + nymph	Mironova & Khorkhordin (1997)
Neemroc EC	Azadirachtin + oil	Field rate	78.3% adult mortality	Knapp & Kashenge (2003)
Neem 1,500 ppm	Azadirachtin	1,500 ppm	50% TSM mortality	Mani et al. (2003)
Pongamia (Pungum oil)	Karanjin, Pongamol	Recommended	~30% mortality	Mani et al. (2003)
Garlic + Chilli 10%	Allicin, Capsaicin	10%	93.91% larval, 65.60% adult	Chandrashekharaiah et al. (2011)
NSKE + *Calotropis* mix	Mixed terpenoids	10%	87.23% larval, 71.70% adult	Chandrashekharaiah et al. (2011)
Ocimum tenuiflorum 10%	Eugenol	10% leaf extract	71.66% mite reduction	Kumar et al. (2009)
Capsicum annum 12%	Capsaicin	12% ethanolic	97% larval, 95% adult	Erdogan et al. (2010)
Lolium perenne/*Chenopodium*	Phenolics/Saponins	5% methanol	> Azadirachtin 10 g/L	Yanar et al. (2011)

VII. ESSENTIAL OILS AND ACARICIDAL ACTIVITY

Essential oils (EOs) are complex volatile mixtures predominantly monoterpenes, sesquiterpenes, and phenylpropanoids produced by aromatic plants as constitutive and induced defences. Their acaricidal mechanisms include acetylcholinesterase inhibition, octopamine receptor antagonism, spiracular blockage, and ovicidal penetration of the chorion (Isman, 2020). Key bioactive compounds include thymol, carvacrol, eugenol, 1,8-cineole, citral, limonene, and linalool.

Deka et al. (2011) demonstrated on cucumber that agricultural spray oil + azadirachtin (0.5–1%) caused the highest *T. urticae* mortality at 24, 48, and 72 hours post-spray in both laboratory and greenhouse trials, illustrating the synergistic value of oil-based botanical carrier systems. Yankova et al. (2009) confirmed that NeemAzal T/S 0.3% and Trilogy 1% (neem-based) showed very good efficacy against spider mites and greenhouse whitefly while maintaining low toxicity to the parasitoid *Encarsia formosa*, validating their suitability for biological vegetable production. Dimetry et al. (2008) reported laboratory evaluation of neem formulations with and without additive against *T. urticae*, confirming enhanced efficacy with oil-carrier combinations.

VIII. MODE OF ACTION OF BOTANICAL ACARICIDES

Unlike synthetic acaricides that typically have a single molecular target site, botanical acaricides deploy multiple overlapping mechanisms, which is their principal advantage in resistance management. The following modes have been documented against *T. urticae*:

- **Contact Toxicity** — Direct cuticle penetration by lipophilic terpenoids, oils, and alkaloids. NeemAzal T/S at 0.5% caused 100% adult contact mortality within 4 days on fig leaves (Mironova & Khorkhordin, 1997).
- **Growth Regulation** — Azadirachtin acts as an ecdysone antagonist disrupting the moulting hormone cascade. At 80 ppm, 50% of *T. urticae* failed to reach the adult stage (Martinez-Villar et al., 2005). The BHU laboratory study confirmed Clofentazine (ovicide) and Azadirachtin (growth regulator) as the top performers against egg and nymph stages respectively (Singh, 2017).
- **Reproductive Inhibition** — Azadirachtin at 64–128 ppm reduced *T. urticae* fecundity significantly, with mean fecundity reduced nearly eightfold in treated females (Martinez-Villar et al., 2005). Kumral and Susurluk (2007) demonstrated that azadirachtin reduced survival and fecundity of a pyrethroid-resistant *T. urticae* population.

- **Repellency and Antifeedancy** — Volatile compounds in garlic, chilli, and essential oils disrupt olfactory and contact chemosensory receptors. Knapp and Kashenge (2003) confirmed that all neem formulations caused repellence in *T. urticae* on tomato leaf discs.

- **Oviposition Deterrence** — Makundi and Kashenge (2002) demonstrated that neem formulations (except Neemros WP) showed strong ovipositional deterrence and suppressed nymph emergence on treated leaf discs. Sundaram (1996) reported AZ-A at sublethal concentrations reduced oviposition and caused growth disruption in *T. urticae* on aspen.

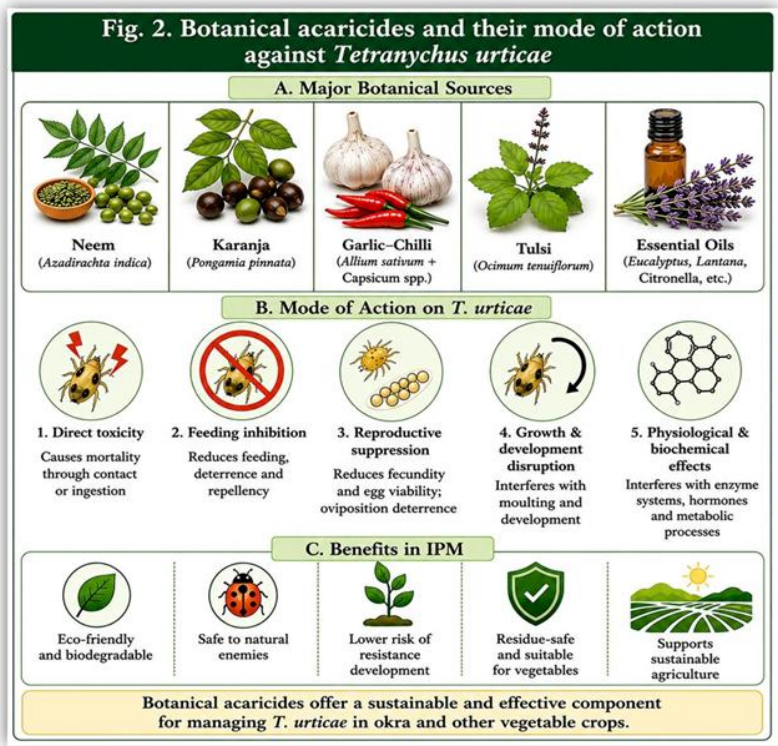

FIGURE 2: Schematic diagram illustrating the multiple modes of action of botanical acaricides against *Tetranychus urticae* Koch, including contact toxicity, growth regulation, reproductive inhibition, repellency, antifeedancy, and oviposition deterrence.

IX. COMPARATIVE EFFICACY: FIELD DATA FROM DOCTORAL INVESTIGATIONS (2013–2017)

The most comprehensive Indian field data on botanical acaricides for *T. urticae* management on okra comes from the multi-year doctoral investigations of Singh (2017) at BHU, Varanasi. Table 3 presents the pooled data from two years of field trials.

TABLE 3
POOLED EFFICACY OF ACARICIDES AGAINST *T. URTICAE* KOCH ON OKRA — BHU, 2013–15 (SINGH, 2017)

Treatment	Category	Pooled % Reduction	Category Rank
Clofentazine 50SC	Synthetic	91.62	1st (synthetic)
Cyflumetofen 20SC	Synthetic	82.52	2nd (synthetic)
Fenpyroximate 5EC	Synthetic	77.48	3rd (synthetic)
Propargite 57EC	Synthetic	72.05	4th (synthetic)
Dicofol 18.5EC	Synthetic	66.92	5th (synthetic)
NSKE 5%	Botanical	50.84	1st (botanical)
Azadirachtin 0.03%	Botanical	49.53	2nd (botanical)
Neem oil 0.03%	Botanical	44.6	3rd (botanical)
P. fumosoroseus (Dust)	Microbial	29.32	1st (microbial)
P. fumosoroseus (EC)	Microbial	22.37	2nd (microbial)
Water spray (control)	Control	11.63	—

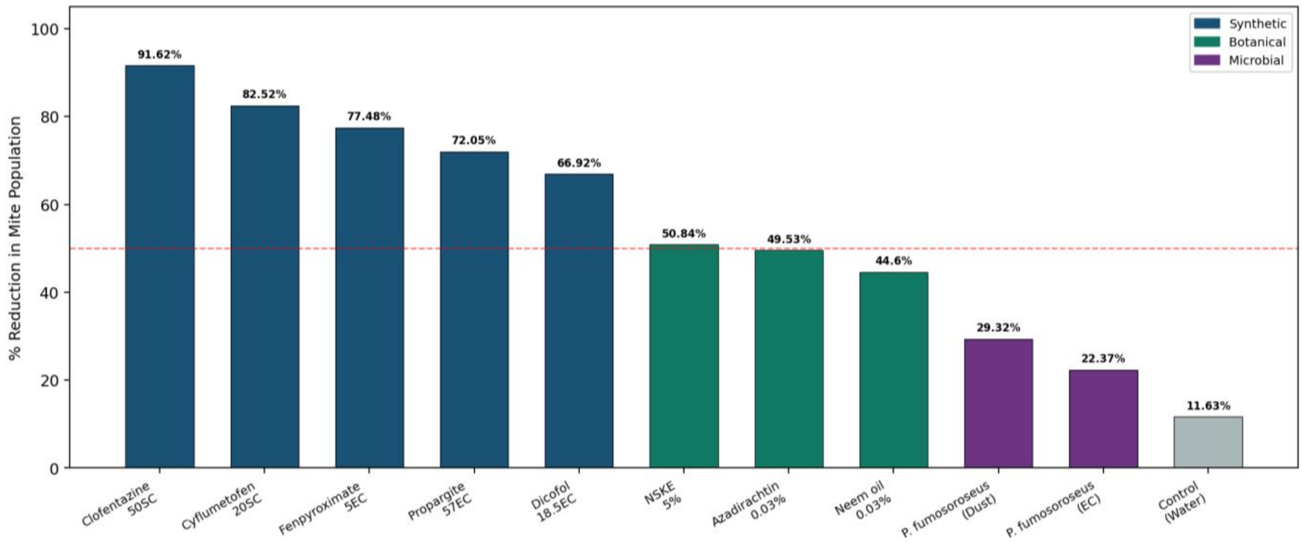

FIGURE 3: Comparative efficacy (% mite reduction) of synthetic, botanical and microbial acaricides against *T. urticae* Koch on okra

X. COMPATIBILITY WITH NATURAL ENEMIES

A decisive advantage of botanical acaricides within IPM is their comparatively low toxicity to natural enemies. Singh and Singh (2005) at Varanasi explicitly demonstrated that azadirachtin and wettable sulfur caused the minimum mortality to the predatory mite *Amblyseius longispinosus* on okra, whereas dicofol and monocrotophos caused maximum predatory mite mortality. This differential selectivity underpins botanical-predator compatibility in IPM frameworks.

Bernardi et al. (2013) demonstrated in Brazilian strawberry that azadirachtin (Azamax® 12 g L^{-1}) did not cause significant mortality in adult *Neoseiulus californicus* or *Phytoseiulus macropilis*, though fecundity was reduced 50%; critically, egg viability exceeded 80%, consistent with control. Azadirachtin's biological persistence (7 days) versus abamectin (21 days) further reduces selection pressure on beneficial arthropods. Abou-Zaid et al. (2012) reported that *P. persimilis* at predator:prey ratios of 1:5 and 1:10 caused 68.60% and 88.20% mean reduction in *T. urticae* respectively—an effect potentially augmented by concurrent sub-lethal botanical treatment. Yankova et al. (2009) confirmed NeemAzal T/S and Trilogy maintained low toxicity to *Encarsia formosa*, qualifying them for biological vegetable production systems.

XI. INTEGRATION WITHIN IPM FRAMEWORKS

Effective botanical-based IPM for okra *T. urticae* should integrate four pillars: (a) host plant resistance—moderately resistant varieties HRB-231, Kashi Sathdhari, Pant-A-4, Kashi Lalima, and Hisar Naveen identified in BHU multi-year screening (Singh, 2017); (b) biological control through conservation of phytoseiid mites and *Stethorus punctillum*; (c) strategic botanical acaricide applications during early or moderate infestations; and (d) judicious use of selective synthetic acaricides (clofentazine, cyflumetofen) only at economic threshold.

For organic okra production, NSKE 5% and azadirachtin 0.03% represent the most field-validated Indian options, achieving around 50% mite suppression with minimum natural enemy disruption (Singh, 2017). Kumar et al. (2009) confirmed CBR values of 1:3.07 for *O. tenuiflorum*-based treatments—economic viability comparable to chemical management. Singh and Singh (1999) demonstrated at Varanasi that azadirachtin 0.03% combined with dicofol at 3+2 ml/litre resulted in 100% mite mortality after 14 days, illustrating the potential of botanical-synthetic mixtures for transitional IPM programmes.

XII. NANOTECHNOLOGY AND FUTURE BOTANICAL FORMULATIONS

Conventional limitations of botanical acaricides—photodegradation, volatility, and inconsistent field performance—can be substantially addressed through nano-encapsulation. Chitosan-based nanoparticles loaded with azadirachtin have shown extended field half-life from 1–2 days to 5–7 days under UV exposure, critical for intense-sun summer okra production in northern India (Bhattacharyya et al., 2016). Nano-emulsions of essential oils in the 20–200 nm size range demonstrate enhanced cuticle penetration, improved rainfastness, and 3–5-fold reduction in effective concentrations compared to bulk formulations

(Isman, 2020). These advances open realistic pathways to botanical acaricides with field persistence and efficacy levels approaching synthetic standards.

XIII. CHALLENGES IN COMMERCIALISATION

Several barriers limit widespread adoption of botanical acaricides for Indian okra *T. urticae* management. The most critical is standardisation: commercial neem formulations vary widely in azadirachtin content (300–10,000 ppm), making dosage recommendations unreliable across brands (Knapp & Kashenge, 2003). Short shelf life due to UV and thermal instability, the regulatory burden of Central Insecticides Board and Registration Committee (CIBRC) registration, and farmer perception that botanicals are 'less effective' than synthetics all constrain market penetration. The moderate efficacy gap—44–51% for botanicals versus 67–92% for synthetics in BHU field trials (Singh, 2017)—must be contextualised: within IPM, botanicals are one component of a multi-tactic system, not standalone chemical substitutes. Extension communication has a vital role in reframing this perception.

XIV. KNOWLEDGE GAPS AND FUTURE RESEARCH PRIORITIES

- Absence of multi-location, multi-year field efficacy data for botanical acaricides across diverse Indian agro-climatic zones (semi-arid Deccan, humid eastern India, and hot arid northwestern plains).
- No standardised bioassay protocol for botanical acaricide evaluation against *T. urticae* comparable to IRAC CM002 for chemical products.
- Synergistic or antagonistic interactions among phytochemical mixtures (neem + garlic; essential oil blends) remain largely uncharacterised using combination index analysis.
- Resistance monitoring in *T. urticae* populations exposed to long-term botanical acaricide use—particularly azadirachtin—has not been systematically carried out.
- Field-level nano-botanical formulation efficacy, phytotoxicity, and environmental fate under Indian conditions remain unvalidated.
- ICT-based and mobile-platform advisory tools for delivering botanical acaricide recommendations to smallholder okra farmers in real time are largely underdeveloped.

XV. CONCLUSION

The findings reviewed in this article indicate that *Tetranychus urticae* continues to be a major constraint to profitable okra cultivation in many production regions. The pest's rapid reproductive capacity, wide host range, and ability to develop resistance to pesticides make its management particularly challenging. Although synthetic acaricides remain effective in reducing mite populations, their long-term sustainability is limited by issues related to resistance, environmental contamination, and adverse effects on non-target organisms.

Evidence generated from laboratory and field studies demonstrates that several botanical products, particularly neem-based formulations, possess significant potential for suppressing spider mite populations. Results obtained from multi-year field investigations at BHU, Varanasi, further support the usefulness of NSKE, azadirachtin, and neem oil as practical management options. In addition to direct toxicity, these products influence mite behaviour, growth, reproduction, and feeding activity, thereby contributing to population suppression through multiple pathways.

Botanical acaricides should not be viewed as complete replacements for synthetic acaricides but rather as important components of an integrated pest management strategy. Their compatibility with biological control agents and lower environmental impact provide clear advantages in sustainable crop production systems. Future research should focus on improving formulation stability, enhancing field persistence, standardising quality parameters, and validating efficacy under different agro-climatic conditions. Strengthening extension efforts and increasing farmer awareness will also be important for promoting wider adoption. With continued scientific refinement and field validation, botanical acaricides can contribute substantially to environmentally responsible and climate-resilient management of spider mites in okra.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The authors alone are responsible for the content and writing of this article.

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