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Integrated Management of *Tetranychus urticae* Koch in Okra: Current Status, Adoption Challenges and Future Perspectives

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Abstract— *Okra (Abelmoschus esculentus L. Moench) is an important vegetable crop cultivated widely in tropical and subtropical regions, with India contributing the largest share of global production. Among the major arthropod pests affecting okra, the two-spotted spider mite, Tetranychus urticae Koch, causes serious economic losses by reducing plant growth, fruit quality, and marketable yield. Effective management of this pest requires an integrated strategy that combines host plant resistance, biological control, cultural practices, judicious use of acaricides, and timely advisory support to farmers. This review critically examines published research on the biology, host range, damage potential, resistance mechanisms, and management approaches for T. urticae in okra. Particular emphasis is placed on integrated pest management (IPM), the role of agricultural extension services, digital advisory systems, and precision agriculture technologies in promoting sustainable mite management. The review also identifies existing research gaps, including the need for standardized resistance-screening methods, economic threshold levels, resistance monitoring, and climate-resilient management strategies. Strengthening collaboration among researchers, extension agencies, and farming communities will be essential for improving the adoption of scientifically validated practices and ensuring sustainable okra production under changing climatic conditions. The findings presented in this review may assist researchers, extension professionals, and policymakers in designing sustainable mite-management programmes suitable for diverse agro-ecological conditions.*

Keywords— Tetranychus urticae, Okra, Integrated pest management, Agricultural extension, Biological control, Host plant resistance, Sustainable agriculture, Two-spotted spider mite, Abelmoschus esculentus, Acaricide resistance, IPM adoption, Farmer Field School.

I. INTRODUCTION

Okra (*Abelmoschus esculentus* (L.) Moench) is among the most economically important warm-season vegetable crops of South Asia and Africa, valued for its nutritive fruit, short duration and export potential. Global production was estimated at approximately 11.2 million tonnes from about 1.14 million hectares in 2022, with India contributing roughly 70% of world output [11]. This dominant and highly concentrated production share (Figure 1) means that pest constraints affecting Indian okra cultivation carry disproportionate weight for global supply, and that management solutions validated under Indian growing conditions have relevance well beyond the country's own borders. The crop is grown predominantly by small and marginal holders, making its pest-management economics inseparable from questions of smallholder cost, labour and access to advisory support.

Besides its economic value, okra contributes significantly to nutritional security and income generation for resource-poor farming households. Therefore, minimizing production losses caused by spider mites is essential not only for improving productivity but also for enhancing farm profitability and livelihood security.

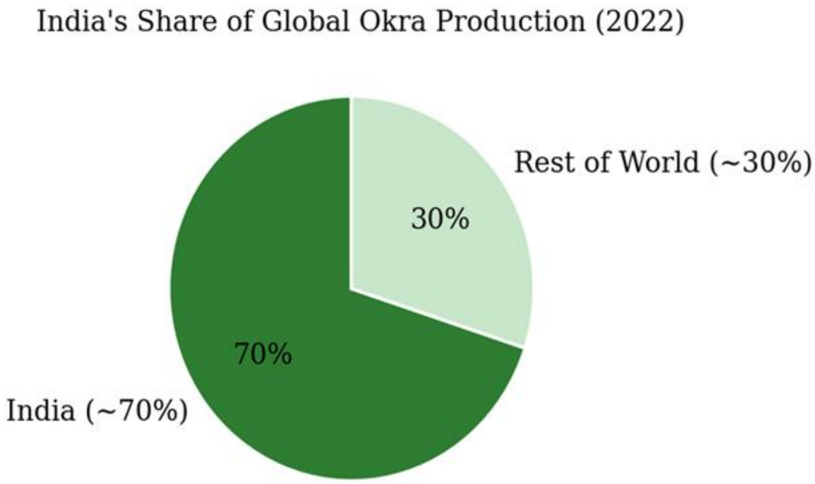


FIGURE 1: India's share of global okra production, 2022 (data: FAO, cited in [11])

Realization of this production potential is persistently constrained by arthropod pests, among which the two-spotted spider mite, *Tetranychus urticae* Koch, ranks as one of the most damaging, with yield losses reported in the range of 7–48% under unmanaged field infestation, and cultivar-wise assessments confirming that susceptible varieties suffer disproportionately greater losses than moderately resistant ones under comparable infestation pressure [30,31]. *T. urticae* is polyphagous and is notorious for the speed with which it evolves acaricide resistance—a trait linked to its short generation time, high fecundity and arrhenotokous reproduction [35]. Repeated, calendar-based chemical spraying, still the default management approach across much of India's vegetable belt, has produced not only resistance but documented resurgence of the pest following certain acaricide applications [21].

This review draws on a doctoral thesis on okra–mite interactions conducted at Banaras Hindu University [32], together with the wider peer-reviewed literature, to synthesize current knowledge of *T. urticae* biology, host-plant resistance and management options in okra, to critically examine the extension and adoption dimension that determines whether laboratory-validated IPM packages reach and are used by farmers, and to outline research gaps and emerging technologies that may reshape mite management over the coming decade.

1.1 Biology, Distribution and Host Range

T. urticae Koch belongs to family Tetranychidae and is commonly termed the two-spotted spider mite for the pair of dark patches visible through the cuticle of feeding females. Its life cycle passes through egg, larva, protonymph, deutonymph and adult stages. Development from larva through deutonymph has been recorded as short as 10 days on a susceptible okra cultivar (Mahyco 10) and as long as 19.8 days on a resistant wild-type accession (Kasturi bhendi), illustrating how host resistance alone can slow developmental rate; fecundity likewise differed sharply by host, at 77.1 eggs/female on the susceptible check versus 41.5 eggs/female on the resistant entry [28]. Feeding occurs through piercing of mesophyll cells, with immature stages generally confined to spongy parenchyma while adults can additionally penetrate palisade tissue [26].

T. urticae has a cosmopolitan distribution across tropical, subtropical and temperate cropping systems worldwide [35]. In India it is reported throughout the major vegetable-growing tracts, with well-documented seasonal build-up in the Gangetic plains, including the Varanasi region where the source thesis work was conducted [12,20,32]. Consistent with its status as one of the most polyphagous arthropod pests known, *T. urticae* has been recorded on vegetables (okra, brinjal, cucumber, tomato, cowpea, bean), fruit crops, cotton and ornamentals, in addition to numerous weed hosts [16,23,25]. Minhajul-Haque et al. [23] recorded the mite on twenty vegetable and twenty-four ornamental species surveyed over a single season in Rajshahi, while Hoque et al. [16] documented differential population build-up on bean, eggplant and okra, with the highest numbers recorded on okra (up to about 174 mites per leaf in August) compared with bean and eggplant in the same survey. This broad host range, together with wind-borne dispersal, complicates area-wide management since untreated alternate hosts continually reseed populations onto the main crop.

The biological characteristics of *T. urticae*, particularly its rapid reproductive capacity and broad host range, enable the pest to establish quickly under favourable environmental conditions. These traits make continuous monitoring essential for timely management.

TABLE 1
REPRESENTATIVE HOST-PLANT CATEGORIES RECORDED FOR *T. URTICAE*, RELEVANT TO OKRA CROPPING SYSTEMS

Host category	Representative species/examples	Source
Vegetables	Okra, brinjal (eggplant), cucumber, tomato, cowpea, bean	[16,23,32]
Fibre crops	Cotton	[25]
Ornamentals	24 ornamental species recorded in a single Rajshahi survey	[23]
Other/weed hosts	Numerous uncultivated field-margin plants	[16,23]

1.2 Economic Importance and Damage Symptoms

Within India's substantial okra production base, *T. urticae* has been identified as one of the most serious pests of the crop, with yield losses of 7–48% reported depending on infestation intensity and cultivar [30,31]. Feeding damage begins as fine chlorotic stippling on the lower leaf surface, progressing to bronzing, leaf curling and premature defoliation under heavy infestation. Quantified in terms of standardized mite-day exposure (a measure combining mite numbers and duration of feeding), net photosynthetic rate in cucumber was reduced by roughly 50% under immature-stage feeding versus roughly 95% under adult-stage feeding at 1,000 mite-days per 6 cm^2 of leaf area, while total chlorophyll content was reduced by roughly 55% and 80%, and overall leaf greenness by roughly 50% and 80%, for immature versus adult feeding respectively at the same exposure level [26]. Because immature mites feed only through the spongy parenchyma while adults can additionally penetrate palisade tissue, damage severity and visibility increase as a colony matures from newly hatched larvae to a mixed-age adult population, meaning that the same numerical mite count can correspond to quite different levels of realized leaf damage depending on the age structure of the population at the time of scouting [26]—a further argument for threshold systems that account for population structure rather than raw mite counts alone. In okra, infested leaves show measurable depletion of nitrogen, phosphorus, potassium, iron, zinc and copper alongside increases in manganese and phenolic content relative to healthy leaves, with the degree of change varying by cultivar and broadly tracking field susceptibility rankings [32]. Because okra is typically grown on small, fragmented holdings and marketed fresh with a short shelf life, even moderate mite-related quality loss can disproportionately affect the farm-gate returns of resource-poor growers.

1.3 Ecology and Population Dynamics

Field studies in the Varanasi region recorded *T. urticae* incidence on okra beginning around the 9th–10th standard week, with the highest phytophagous mite population per 2.5 cm^2 leaf area recorded at 47.75 mites in the 21st standard week during one crop season and 45.99 mites in the 18th standard week during the following season—in both cases coinciding with the hot, dry conditions of May—alongside a significant positive correlation with mean temperature, sunshine hours and wind velocity, and a negative correlation with relative humidity and rainfall [20]. A separate doctoral study on the ecology and management of *T. urticae* on okra similarly framed seasonal population build-up as driven primarily by temperature and moisture regime [12]. This temperature-driven pattern is consistent with the wider literature: spider mite populations generally develop and reproduce faster under hot, dry conditions, and warming, drier conditions are broadly expected to intensify outbreak frequency in several *Tetranychus* species [3]. This has direct implications for okra, itself a hot-season crop whose cultivation window overlaps closely with periods of peak mite pressure.

Seasonal monitoring of mite populations can support timely interventions and reduce unnecessary acaricide applications. Integrating weather-based forecasting with field scouting may further improve decision-making under changing climatic conditions.

II. MATERIALS AND METHODS

This study follows a narrative review approach in which published scientific literature and authenticated documentary sources were critically examined, compared, and synthesized to develop a comprehensive understanding of spider mite management in okra.

2.1 Primary Source

The principal source underlying the biology, host-plant resistance, biochemical, and acaricide-efficacy content of this review is a doctoral thesis on the screening of okra varieties against *T. urticae* and its management, submitted to the Department of Entomology & Agricultural Zoology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi [32]. Data drawn from this thesis include field screening of sixteen okra varieties over two seasons (2013–14 and 2014–15), biochemical estimation of healthy versus mite-infested leaves, and a two-year pooled field evaluation of synthetic, botanical and microbial acaricides, including a dedicated resurgence assessment.

2.2 Literature Search and Selection

Supplementary peer-reviewed literature was identified through targeted searches using combinations of the terms "*Tetranychus urticae*", "okra", "*Abelmoschus esculentus*", "host plant resistance", "acaricide resistance", "integrated pest management adoption", and "agricultural extension". Sources were included only where they could be independently identified and verified (author, year, and outlet); where a specific statistic or claim could not be traced to a verifiable source, it was excluded from the review rather than estimated. This approach necessarily limits the reference base to a curated set of thirty-seven sources rather than an exhaustive bibliometric sample, and the review should be read with that scope in mind.

2.3 Synthesis Approach

Findings from the thesis and the supplementary literature were organized thematically—biology and ecology, host-plant resistance and its biochemical basis, integrated pest management components, farmer adoption barriers, and the role of agricultural extension—and cross-compared to identify points of agreement, disagreement, and gaps in the existing evidence base, which are reported in Section III and summarized as explicit research gaps.

2.4 Scope and Limitations

This review deliberately weights its synthesis toward a single doctoral thesis conducted at one Indian university [32], supplemented by thirty-six independent sources; readers should therefore treat cultivar-resistance rankings, biochemical figures and acaricide-efficacy data reported here as representative of the Varanasi agro-climatic region and the specific trials cited, rather than as universally generalizable across every okra-growing tract. Similarly, the extension analysis in Sections 3.4–3.5 draws on a curated set of institutional and international IPM-adoption sources, but district- or block-level, okra-mite-specific adoption studies were not identified in the literature reviewed and would strengthen future work. Statistics and figures presented throughout are drawn directly from the cited sources; where a specific claim could not be traced to a verifiable source within this curated reference set, it has been omitted or flagged as a gap (Section 3.6) rather than filled with an estimated value. Because several of the technology-related sources in this review (drones, resistance-monitoring genomics) are recent and rapidly evolving fields, their application specifically to *T. urticae* on okra should be read as an identified opportunity rather than an established, field validated practice.

III. RESULTS AND DISCUSSION

3.1 Screening of Resistant Okra Varieties

The source thesis screened sixteen okra varieties under field conditions over two seasons (2013–14 and 2014–15) and categorized them by mean mite population into susceptible, moderately susceptible and moderately resistant groups. HRB-231, Kashi Sathdhari, Pant-A-4, Hisar Naveen and Kashi Lalima were classed as moderately resistant, while Azad Bhindi-1, Varsha Uphar, Punjab Padmini and Panjab-7 were most susceptible [32]. A significant negative correlation was found between mite population and both trichome number ($r = -0.71$) and yield per plant ($r = -0.49$) across both seasons [32].

This trichome-mediated resistance pattern is corroborated by independent work: Manual et al. [22] found Arka Anamika and D-1-87-5 resistant among seven okra lines screened against the related species *T. neocaledonicus* at Pusa, while Roseleen and Ramaraju [29] identified the wild-type accession Kasturi bhendi as consistently the most resistant okra entry against *T. urticae*, with Dharmapuri Local, Parbani Kranti, Pusa Sawani and COBhH1 rated moderately resistant and the commercial cultivar Mahyco 10 remaining susceptible across multiple independent trials [28,29,30]. Guo and Yue [14] provide a broader mechanistic review showing that leaf trichomes affect mite populations both physically—by impeding movement, providing camouflaging shelter, and altering the leaf microenvironment—and chemically, through defense compounds either present in trichomes or induced upon attack, which can also serve as cues that attract predatory mites to infested leaves.

Cultivar rankings are not perfectly comparable across studies, nevertheless, because screening methodology differs. East et al. [8] compared whole-leaf, floating-disc and clip-cage techniques for screening muskmelon resistance to *T. urticae* and found that coefficient-of-variation values were similar for the whole-leaf and floating-disc methods but substantially lower than for the clip-cage method, with resistant melon lines (including accessions labelled BUS, CHI, PI 164343 and PI 17895 in that study) identified consistently across both of the more reliable techniques. This methodological inconsistency is worth flagging as a limitation when comparing okra resistance rankings across research groups that may not have used equivalent screening protocols.

TABLE 2
SELECTED OKRA GENOTYPES AND THEIR REPORTED RESISTANCE RESPONSE TO *TETRANYCHUS* SPP.

Genotype	Reported response	Source
Kasturi bhendi (wild type)	Resistant	[28,29,30]
Dharmapuri Local, Parbani Kranti, Pusa Sawani, COBhH1	Moderately resistant	[29,30]
HRB-231, Kashi Sathdhari, Pant-A-4, Hisar Naveen, Kashi Lalima	Moderately resistant	[32]
Arka Anamika, D-1-87-5	Resistant (vs. *T. neocaledonicus*)	[22]
Mahyco 10	Susceptible	[28,29,30]
Azad Bhindi-1, Varsha Uphar, Punjab Padmini, Panjab-7	Susceptible	[32]

Beyond the trichome and yield correlations reported above, the same two-season thesis dataset found a significant positive correlation between mite population and the number of leaves per branch ($r = 0.46$), a non-significant positive correlation with number of primary branches ($r = 0.17$), and non-significant negative correlations with days to 50% flowering ($r = -0.12$), plant height ($r = -0.42$), number of flowers ($r = -0.21$), fruit length ($r = -0.19$), number of fruits per plant ($r = -0.46$) and fruit diameter ($r = -0.18$) [32]. The pattern—strong, significant associations for trichome number and yield, but weaker or non-significant associations for most other morphological and phenological traits—supports treating trichome density specifically, rather than general plant vigour or architecture, as the primary morphological resistance trait worth prioritising in okra breeding programmes.

TABLE 3
CORRELATION BETWEEN *T. URTICAE* POPULATION AND OKRA PLANT/YIELD TRAITS (POOLED TWO-SEASON FIELD DATA)

Plant/yield trait	Correlation coefficient (r)	Significance
Number of trichomes	−0.71	Significant
Yield per plant	−0.49	Significant
Number of fruits per plant	−0.46	Non-significant
Plant height	−0.42	Non-significant
Number of flowers	−0.21	Non-significant
Fruit length	−0.19	Non-significant
Fruit diameter	−0.18	Non-significant
Number of primary branches	0.17	Non-significant
Days to 50% flowering	−0.12	Non-significant
Number of leaves per branch	0.46	Significant

Source: [32]. Note the divergent behaviour of the two significant traits: higher trichome number is associated with lower mite population (consistent with a protective, antixenotic role), whereas a higher number of leaves per branch is associated with higher mite population, plausibly reflecting the additional feeding surface and microclimate that denser foliage provides.

3.2 Biochemical Basis of Resistance

Biochemical estimation in the thesis showed that mite-infested okra leaves lost nitrogen, phosphorus, potassium, iron, copper and zinc relative to healthy leaves, while manganese content increased [32]. Independent studies on other hosts show a consistent pattern: Ghoshal [13] reported chlorophyll, protein, carbohydrate and several micronutrients depleted in mite-infested Tulsi leaves, with phenol content rising by over 30%; Barman and Ghoshal reported comparable depletion patterns in chilli [5] and coconut [4], with phenol again the one compound that consistently increased with mite feeding. This convergence across unrelated host species indicates that phenolic and tannin accumulation is a general induced-defense response to *Tetranychus* feeding rather than an okra-specific mechanism.

Roseleen and Ramaraju's screening of okra entries against *T. urticae* found that the reduction in leaf moisture content on infestation was greatest (about 15.3%) in the susceptible check and smallest in resistant entries, while resistant wild-type Kasturi bhendi recorded the highest total phenol content of any entry in both healthy (6.23 mg/g) and infested (about 9.50 mg/g) leaves, alongside roughly 20% higher tannin content than mite-free plants of the same entry [29,30]. Infested plants generally recorded lower total protein than mite-free plants, whereas total free amino acids were higher in infested plants than in mite-free ones, and mite feeding was associated with increased peroxidase, polyphenol oxidase and phenylalanine ammonia lyase activity in the resistant entries specifically [29,30]—enzyme markers consistent with an induced, rather than purely constitutive, biochemical defense response.

A more complex picture emerges from Hildebrand et al.'s soybean study [15], in which the cultivars 'Bonus' and 'Williams' were infested with 0, 10 and 200 mites per leaf at the V3, V6 and R2 growth stages: the cultivar showing greater relative resistance ('Williams', which sustained significantly lower mite population increase than 'Bonus') also showed the larger relative loss of leaf chlorophyll (about 55%) and an even larger loss of carotenoid content (about 79%) at the lower mite-infestation level, attributed to a stronger hypersensitive oxidative response. This raises an open question for okra breeding: resistance measured as lower mite numbers does not automatically imply proportionally lower biochemical damage per mite, and the two should be evaluated together rather than resistance being inferred from population counts alone.

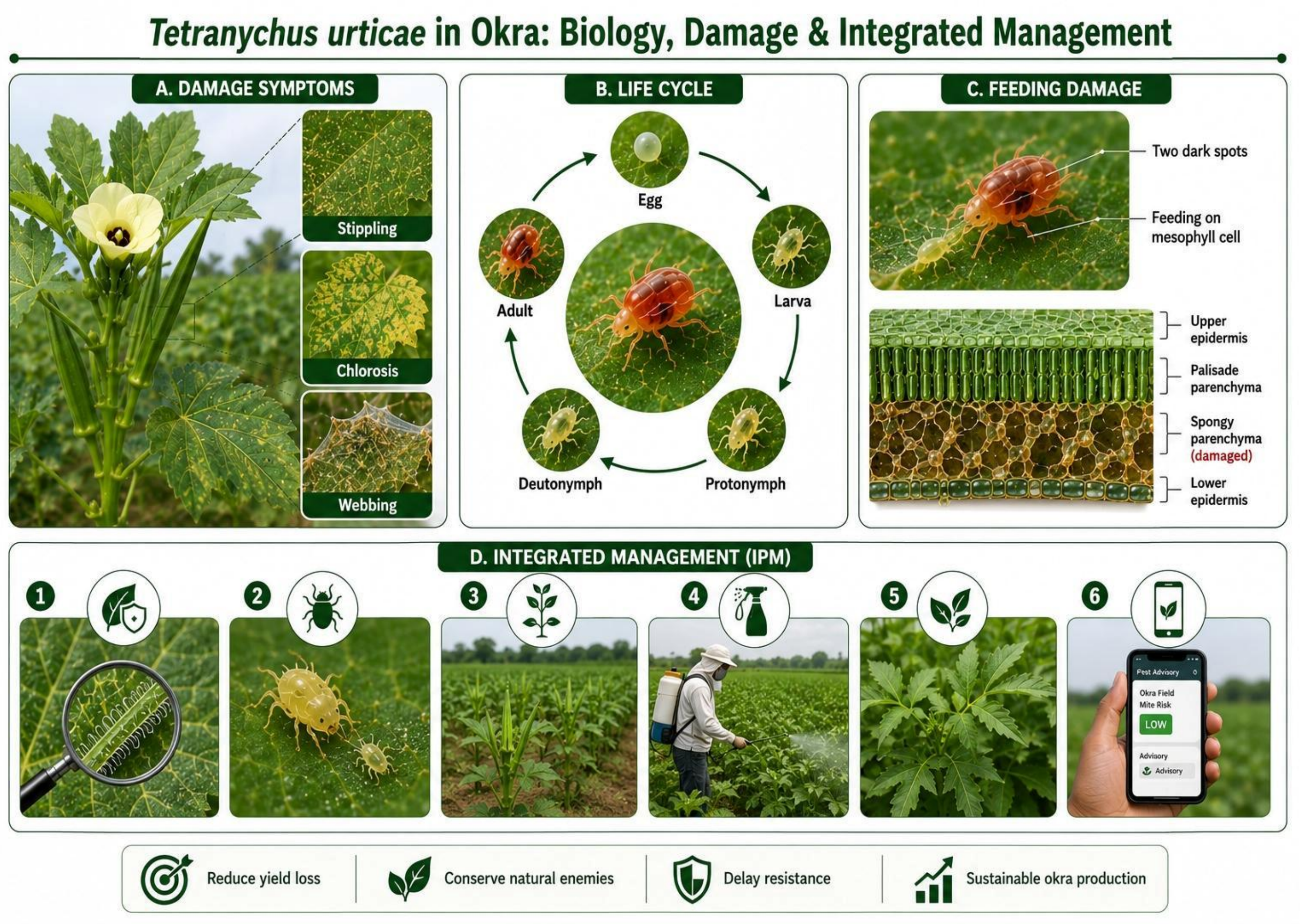
Across the sixteen okra varieties screened in the source thesis, the range of biochemical depletion on mite infestation gives a sense of the variation among genotypes: leaf nitrogen loss ranged from about 1.52% (Azad Bhindi-1) to 1.76% (Panjab-7); phosphorus loss ranged from about 0.16% (Varsha Uphar) to 0.23% (Punjab Padmini); potassium content in infested leaves ranged from about 1.94% (Azad Bhindi-1) to 2.44% (Panjab-7), with the percentage decrease relative to healthy leaves ranging from about 0.44% to 0.72% depending on variety; iron content showed a percentage decrease ranging from about 2.74% (Pusa

Sawani) to 18.60% (HRB-231); zinc content decreased by about 33.5% to 39.5% depending on variety; and copper content decreased by about 24.9% to 37.8% depending on variety, while manganese content increased on infestation across all varieties tested, ranging from about 57.6 to 61.0 mg/kg [32].

TABLE 4
RANGE OF BIOCHEMICAL DEPLETION IN MITE-INFESTED OKRA LEAVES ACROSS SIXTEEN SCREENED VARIETIES

Biochemical parameter	Range across varieties	Direction of change
Nitrogen (N)	1.52% – 1.76%	Depletion
Phosphorus (P)	0.16% – 0.23%	Depletion
Potassium (K), % decrease	0.44% – 0.72%	Depletion
Iron (Fe), % decrease	2.74% – 18.60%	Depletion
Zinc (Zn), % decrease	33.5% – 39.5%	Depletion
Copper (Cu), % decrease	24.9% – 37.8%	Depletion
Manganese (Mn)	57.6 – 61.0 mg/kg	Increase

Source: [32], pooled data from field seasons 2013–14 and 2014–15. The consistent direction of change across all sixteen varieties—depletion of N, P, K, Fe, Zn and Cu alongside a consistent increase in Mn—suggests a shared physiological response to mite feeding across genotypes, even though the magnitude of change (and hence the biochemical "cost" of infestation) differs by variety.



Source: Prepared by the authors based on the published literature cited in this review; icons and layout are illustrative and not reproduced from any single source

3.3 Integrated Pest Management

A quantified economic injury level (EIL) of 1.31–1.52 mites/inch² has been established for *T. urticae* on cucumber under plastic-house conditions, based on a two-season trial in which artificial infestation at rates of 1, 2, 5 and 10 mites/inch² produced yield reductions ranging from about 18% to 54% in the first season and about 20% to 57% in the second, relative to an uninfested control [9]. No analogous, validated threshold specific to *T. urticae* on okra was identified in the reviewed literature—a significant practical gap, since without a threshold, spray decisions on farmers' fields default to calendar schedules rather than population-triggered intervention.

TABLE 5
MITE INFESTATION RATE AND CORRESPONDING YIELD REDUCTION IN CUCUMBER, INFORMING THE ECONOMIC INJURY LEVEL (EIL) CONCEPT

Infestation rate (mites/inch²)	Yield reduction, Season 1 (%)	Yield reduction, Season 2 (%)
1	18	20.5
2	28.2	32.2
5	38.9	45.1
10	54	56.6

Source: [9]. No comparable infestation-rate/yield-loss trial for T. urticae on okra was identified, underscoring the research gap noted in Section 3.6.

Because mite populations build up faster under hot, dry conditions, cultural measures that maintain adequate crop humidity and avoid moisture stress can help suppress early-season build-up [3,20]. Among biological agents, the predatory mite *Phytoseiulus persimilis* achieved 68.6–88.2% population reduction at release ratios of 1:5 and 1:10 (predator:prey) against *T. urticae* on eggplant [1]. Beyond Phytoseiid mites, soil-dwelling predatory mites of the genus *Hypoaspis* have shown biocontrol potential against related mite pests, though their predatory efficacy was found to be temperature-dependent and reduced by the presence of alternative prey in laboratory assessment [2]—a caution relevant to any field release programme, since okra fields rarely host a single prey species in isolation.

Compatibility between acaricides and biological control agents varies substantially by product and needs to be assessed alongside raw mite-mortality data. Azadirachtin caused negligible direct mortality to the predatory mites *Neoseiulus californicus* and *Phytoseiulus macropilis* in strawberry, with egg viability in treated plots remaining above 80% (similar to untreated controls), though it still reduced predator fecundity by about half; importantly, azadirachtin's biological persistence in that trial (about 7 days) was considerably shorter than that of abamectin (about 21 days), meaning any negative effect on the predators was also comparatively short-lived [6]. Among acaricides tested against *T. urticae* in citrus orchards, mineral oil, tebufenpyrad and clofentezine were found harmless to the parasitoid *Aphidius colemani*, whereas fenazaquin was moderately harmful to the predatory mite *Neoseiulus californicus* specifically, illustrating that natural-enemy compatibility cannot be assumed to be uniform even among acaricides with similar target-pest efficacy [34]. Selecting acaricides for both efficacy and natural-enemy compatibility is consequently a distinct decision from selecting for mite mortality alone.

In the pooled two-year thesis field trial, botanical formulations gave moderate control—NSKE (5%) reduced mite numbers by 50.8%, azadirachtin (0.03%) by 49.5%, and neem oil (0.03%) by 44.6%—while microbial formulations of *Paecilomyces fumosoroseus* performed comparatively poorly under field conditions (22.4–29.3% reduction) [32]. Independent screening of plant extracts against *T. urticae* found that *Lolium perenne*, *Anthemis vulgaris* and *Chenopodium album* extracts produced considerably higher adult mortality than azadirachtin at the concentrations tested [37], indicating that botanical efficacy varies considerably by plant source and is not yet standardized.

Newer acaricide chemistries substantially outperformed older standards in the thesis trial: clofentazine gave the highest mite reduction (91.6%), followed by cyflumetofen (82.5%), fenpyroximate (77.5%), propargite (72.1%) and dicofol (66.9%) [32]. In a separate laboratory evaluation of acaricides against *T. urticae* on cotton, chlorfenapyr, pyridaben and fenpyroximate were the most effective miticides overall, with chlorfenapyr producing 87–100% mortality in both laboratory and field assessments, while dicofol was the least effective of the compounds tested (32–38% mortality); fenpyroximate additionally recorded the lowest LC50 value (about 5.18 mg/L) among the acaricides evaluated in that study [25], reinforcing the pattern of dicofol's comparatively weak field performance seen in the okra thesis data.

Resistance to acaricides in *T. urticae* arises through a combination of target-site mutations that reduce the sensitivity of the acaricide's binding site and metabolic detoxification via enhanced activity of detoxifying enzyme families, mechanisms that have been documented across numerous acaricide classes and mite populations worldwide [35]. Widely reported dicofol resistance in *T. urticae* populations illustrates how persistent such resistance can be: laboratory-selected resistance of about 23-fold was maintained for a full year even after selection pressure was removed, declining only to about 15.8-fold after two years and 10.7-fold after three years without further dicofol exposure [19]—indicating that resistance, once established in a field population, is not expected to reverse quickly even if the compound is temporarily withdrawn from use. This reinforces the case for rotating modes of action rather than repeated use of a single acaricide class.

TABLE 6
DECLINE IN DICOFOL-RESISTANCE LEVEL OF *TETRANYCHUS URTICAE* OVER TIME WITHOUT FURTHER SELECTION PRESSURE

Time since selection halted	Resistance level (fold, relative to susceptible strain)
1 year	~23.0-fold
2 years	~15.8-fold
3 years	~10.7-fold

Source: [19]. The gradual, incomplete decline illustrated in Table 6 underlines why acaricide-resistance management works best as a preventive rotation strategy rather than a reactive one.

Critically, only dicofol among the compounds tested in the thesis trial triggered pest resurgence in the resurgence-specific assessment, while clofentazine, cyflumetofen, fenpyroximate and propargite did not [32]. This echoes the broader mechanism documented for resurgence in other sucking pests: repeated organophosphate, carbamate or pyrethroid use has been shown to induce resurgence primarily through insecticide-driven changes in host-plant chemistry—particularly nutritional status—following application, sometimes accompanied by increased fecundity, a shortened nymphal period, and an altered sex ratio favouring the pest, whereas neonicotinoids, insect growth regulators and botanicals have generally not induced comparable resurgence in the sucking-pest systems studied [33].

TABLE 7
COMPARATIVE EFFICACY OF SYNTHETIC, BOTANICAL AND MICROBIAL PESTICIDES AGAINST *T. URTICAE* ON OKRA (POOLED TWO-YEAR FIELD DATA)

Treatment	Mean mite reduction (%)	Resurgence observed?
Clofentazine 50 SC	91.6	No
Cyflumetofen 20 SC	82.5	No
Fenpyroximate 5 EC	77.5	No
Propargite 57 EC	72.1	No
Dicofol 18.5 EC	66.9	Yes
NSKE 5%	50.8	—
Azadirachtin 0.03%	49.5	—
Neem oil 0.03%	44.6	—
Paecilomyces fumosoroseus (dust)	29.3	—
Paecilomyces fumosoroseus (EC)	22.4	—

Source: [32], pooled data from field seasons 2013–14 and 2014–15. "—" indicates resurgence was not separately assessed for that treatment in the pooled trial.

The same thesis also examined efficacy separately by mite life stage—egg, nymph, adult male and adult female—under laboratory conditions, releasing each stage onto treated okra leaf surfaces and recording mortality up to 72 hours after treatment [32]. Clofentazine gave the highest mortality at every stage examined (egg 99.9%, nymph 100%, adult male 99.9%, adult female 86.6%), whereas neem oil and azadirachtin were consistently the weakest performers, with neem oil giving only 32.6% egg mortality and 8.25% nymph mortality, and azadirachtin giving only 36.8% adult-male mortality [32]. Adult females were the life stage most tolerant of treatment across almost all products tested, including the most effective compound, suggesting that a single spray timed against egg or nymph populations is likely to leave a partially surviving adult-female cohort capable of resuming oviposition—reinforcing the case for repeat or overlapping applications rather than a single intervention, regardless of which acaricide is chosen.

TABLE 8
LIFE-STAGE-WISE MORTALITY OF *T. URTICAE* UNDER LABORATORY BIOASSAY, 72 HOURS AFTER TREATMENT (SELECTED TREATMENTS)

Treatment	Egg (%)	Nymph (%)	Adult male (%)	Adult female (%)
Clofentazine 50 SC	99.9	100	99.9	86.6
Azadirachtin 0.03%	—	—	36.8	—
Neem oil 0.03%	32.6	8.3	—	38.2

Source: [32]. "—" indicates the treatment was not among the highest/lowest performers reported for that particular life stage in the thesis summary and is omitted here rather than estimated.

TABLE 9
COMPARISON OF MAJOR MANAGEMENT OPTIONS FOR *T. URTICAE* IN OKRA: ADVANTAGES AND LIMITATIONS

Management option	Advantages	Limitations
Host-plant resistance (trichome-rich cultivars)	Chemical-free; persistent across the season	Resistant cultivars not universally available; screening methods inconsistent across studies [8]
Biological control (Phytoseiid predators, *Hypoaspis* spp.)	Self-sustaining once established; compatible with several botanicals	Predator availability limited at village level; sensitive to broad-spectrum sprays [1,2,6,34]
Botanical acaricides (azadirachtin, NSKE, neem oil)	Low mammalian toxicity; safer for natural enemies	Moderate, variable field efficacy (~44–51% reduction) [32]
Microbial acaricides (entomopathogenic fungi)	Environmentally benign; fits organic production	Weakest field performance among options tested (~22–29% reduction) [32]
Selective synthetic acaricides (clofentazine, cyflumetofen, fenpyroximate)	Highest field efficacy (77–92% reduction); no resurgence observed [32]	Cost and availability constraints at farm level [7]
Legacy acaricides (dicofol)	Low unit cost; widely available	Triggers resurgence; documented resistance persisting a year or more [19,32]

3.4 Farmer Adoption Challenges

Even where research demonstrates that IPM packages combining host resistance, biological control and selective acaricides outperform calendar spraying, adoption on Indian okra farms lags. A broad review of global IPM adoption identifies technical complexity, insufficient training investment, weak confidence in decision-support information, and a persistent gap between farmers recognizing IPM's value and actually sustaining its use, as recurring barriers across cropping systems [7]. Several of these barriers apply directly to okra:

- **Knowledge and awareness:** Farmer knowledge of economic thresholds is limited by the absence of a validated threshold for this crop (Section 3.3), and awareness of *T. urticae* as distinct from other okra pests such as jassids and whitefly is often incomplete, since early stippling damage is easily overlooked until populations are already substantial [7].
- **Cost and availability:** Newer, more effective acaricide chemistries and biological control agents are not always accessible to small and marginal farmers at village level, compared with widely stocked legacy compounds such as dicofol, restricting practical choice regardless of awareness [7].
- **Training:** Scouting and threshold-recognition skills are a prerequisite for any monitoring-based alternative to calendar spraying, and one-off input distribution without accompanying training tends not to translate into sustained behaviour change [7].
- **Socio-economic constraints and extension delivery:** Smallholding size and the labour demands of monitoring-based IPM relative to calendar spraying can make even a technically superior package less attractive to resource-constrained households in the short run, while weak confidence in decision-support information points to extension delivery itself, not merely farmer knowledge, as a limiting factor [7]. Because okra is grown predominantly by resource-constrained households, the socio-economic and extension-delivery dimensions of adoption are as consequential as the underlying technical options themselves.

The successful adoption of IPM technologies depends not only on the availability of effective management options but also on continuous farmer education, local demonstrations, and access to reliable advisory services. These factors collectively influence long-term adoption behaviour.

3.5 Role of Agricultural Extension

Because the preceding section shows that adoption barriers are as much institutional as technical, this section reviews the specific mechanisms through which validated okra-mite IPM could realistically reach farmers. The Farmer Field School (FFS) model—participatory, season-long, discovery-based learning conducted directly in farmers' own fields rather than through top-down instruction—was developed as a response to insecticide-induced pest outbreaks and has since been documented across a large number of low- and middle-income countries, with a systematic review estimating some 10–20 million farmer graduates worldwide [36]; the same systematic review notes that while FFS participation is associated with improved farmer knowledge and, in many studies, reduced pesticide use, the certainty of evidence for yield and income outcomes is more mixed across the studies it assessed, underlining that FFS-style extension is a promising but not unconditionally guaranteed route to behaviour change [36]. The approach has been formally promoted as a route "from farmer field school to community IPM" by the FAO's regional office for Asia and the Pacific [10]. Although most documented FFS work centres on rice IPM in Asia, the same participatory logic is directly transferable to vegetable IPM: building farmer capacity to distinguish phytophagous mites from beneficial predatory mites, to recognize early stippling and webbing, and to make spray decisions based on field observation rather than the calendar.

India's Kisan Call Centre (KCC) scheme provides toll-free, multilingual telephone advisory to farmers, with unresolved queries escalated to subject-matter specialists [24], and the complementary mKisan portal delivers SMS- and voice-based advisories drawing on the same institutional network [27]. Neither platform was documented in the reviewed literature as currently carrying okra-mite-specific advisory content, pointing to a content gap rather than a platform-availability gap—the institutional channel already exists and reaches farmers at scale.

Beyond telephone- and SMS-based advisory, precision technologies such as unmanned aerial vehicles equipped with multispectral, thermal or hyperspectral imaging sensors are increasingly recognized as innovative tools for precision pest management, particularly valuable where infestations are patchy or pests are too small to see readily by eye [18]—conditions that describe early-stage *T. urticae* stippling on okra reasonably well. Extending such precision-technology approaches, or the

FFS/KCC/mKisan channels already reaching Indian farmers, to carry okra-mite-specific, threshold-based advisory content represents a concrete, near-term opportunity rather than a distant prospect.

Strengthening collaboration among research organizations, extension agencies, input suppliers, and farmer groups will improve the dissemination of location-specific recommendations and encourage wider adoption of integrated mite management practices.

TABLE 10
EXTENSION APPROACHES RELEVANT TO OKRA–MITE IPM TECHNOLOGY TRANSFER

Approach	Mechanism	Relevance to okra–mite IPM	Source
Farmer Field School (FFS) / community IPM	Season-long, participatory, discovery-based learning in-field	Model for building scouting and threshold-recognition skill; not yet institutionalized for Indian vegetable IPM	[10,36]
Kisan Call Centre (KCC)	Toll-free, multilingual telephone advisory	Could carry okra-mite advisory; no such content documented yet	[24]
mKisan portal	SMS / voice location- and language-specific advisory	Same institutional reach as KCC; content gap for mite-specific advisory	[27]
UAV / precision pest-management technology	Imaging sensors for early, localized pest detection	Suited to patchy, hard-to-scout infestations; not yet applied to okra mite specifically	[18]

TABLE 11
RECENT STUDIES (2020–2025) INFORMING THE TECHNOLOGY AND FUTURE-PERSPECTIVE CONTENT OF THIS REVIEW

Year	Focus	Key relevance to okra–mite IPM	Source
2020	Drone-based precision pest management technology	UAV imaging suited to patchy, hard-to-scout infestations	[18]
2021	Global review of IPM adoption barriers	Frames technical, training and cost barriers relevant to okra IPM adoption	[7]
2024	Water stress, temperature and outbreak potential in spider mites	Confirms warming, drier conditions raise mite outbreak risk, with specialist/generalist species differing in response	[3]
2025	Acaricide resistance monitoring and structural/genomic insights	Molecular basis for resistance-informed acaricide rotation	[17]
2025	Okra production constraints and opportunities, global review	Source of global production and India's production-share statistics used in Section I	[11]

3.6 Research Gaps

Several gaps emerge from this synthesis: (i) no economic injury level or action threshold specific to *T. urticae* on okra has been established, unlike the quantified EIL documented for cucumber [9]; (ii) resistance-screening methodologies vary widely across studies, limiting direct comparability of "resistant" cultivar rankings between research groups [8]; (iii) the relationship between host-plant resistance and induced biochemical defense is not fully reconciled, since some resistant entries show larger relative biochemical shifts than susceptible ones [15]; (iv) extension research on okra-specific IPM adoption in India is sparse compared with the broader IPM-adoption literature [7]; (v) no published work was identified that integrates precision or digital pest-surveillance tools specifically for smallholder okra–mite management, despite the demonstrated general applicability of such tools to comparably patchy pest problems [18]; (vi) the specialist-versus-generalist difference in climate-driven outbreak potential documented for spider mites generally has not been examined specifically for *T. urticae* on okra under Indian field conditions [3]; and (vii) although trichome number and yield per plant show significant, consistent correlations with mite population across the varieties tested, most other morphological and phenological traits show weak or non-significant associations, and the underlying physiological basis for why leaf-density traits (leaves per branch) correlate positively with mite population while trichome density correlates negatively continues to be mechanistically unexplained [32].

3.7 Future Perspectives

Genomic and structural approaches are clarifying acaricide-resistance mechanisms at the molecular level; recent work combining bioassays with mutation screening and structural analysis has mapped resistance-associated mutations—for example in the voltage-gated sodium channel and cytochrome b genes—across *T. urticae* field populations, offering a route toward resistance-informed acaricide rotation rather than trial-and-error spraying [17]. Precision pest-management technologies, including UAV-based multispectral, thermal and hyperspectral imaging already used for early detection of patchy infestations in other cropping systems, represent a plausible extension to okra-mite surveillance, though validated applications specific to *T. urticae* remain to be developed [18].

Climate-resilient IPM will also need to account for the likely intensification of mite pressure under warming, drier conditions: a comparative study of a specialist and a generalist spider mite species found that water-stressed host plants and elevated temperature both increased outbreak potential, though the magnitude of the effect differed between the specialist and generalist species examined, indicating that climate-driven outbreak risk may not be uniform across *Tetranychus* species and host-plant combinations [3]. Future research should also focus on validating digital decision-support systems under farmers' field conditions and evaluating their economic feasibility for smallholder vegetable production systems.

This reinforces the case for breeding trichome-rich, drought-tolerant okra cultivars that combine mite resistance with resilience to the same hot, dry conditions that favour mite population growth. Taken together, resistance-mechanism monitoring, precision surveillance technology, and continued investment in host-plant resistance breeding represent a plausible, though still developing, path toward reducing reliance on synthetic acaricides in okra–mite management over the coming decade.

IV. CONCLUSION

T. urticae remains a persistent constraint on okra productivity, with documented yield losses, well-characterized biology, and a growing though fragmented body of work on varietal resistance, biochemical defense and acaricide efficacy. The doctoral thesis synthesized here indicates that newer acaricide chemistries (clofentazine, cyflumetofen, fenpyroximate) substantially outperform legacy compounds such as dicofol, which additionally triggers resurgence and whose resistance, once established, declines only slowly even after selection pressure is removed [19,32]. Trichome-mediated host resistance offers a complementary, chemical-free line of defense, corroborated across independent screening studies despite methodological differences between them [8,14,22,28,29,30,32].

Yet translation of this research base into farmer practice is constrained less by a shortage of technical options than by adoption barriers—knowledge, cost, training, and socio-economic and extension-delivery constraints documented in the wider IPM literature but under-studied specifically for Indian okra systems [7]. Encouragingly, mechanisms already exist that could carry validated okra-mite IPM to farmers—Farmer Field School-style participatory learning, the Kisan Call Centre and mKisan advisory network, and precision surveillance technologies [10,18,24,27,36]—such that closing the gap between research and practice is substantially a content and validation challenge: populating these existing channels with okra-mite-specific, threshold-based advisory material, while continuing to invest in resistance-mechanism monitoring and trichome-based breeding for a warmer, drier future [3,17].

The findings synthesized in this review emphasize that future progress in spider mite management will depend on integrating biological knowledge with practical extension strategies. Strengthening collaboration among researchers, extension professionals, policymakers, and farmers will facilitate wider adoption of integrated pest management practices and improve the long-term sustainability of okra production systems.

Overall, sustainable management of *T. urticae* will require an integrated approach that combines scientific innovation, farmer participation, and effective extension support. Continued investment in research, capacity building, and climate-smart pest management strategies will be essential for maintaining profitable and environmentally sustainable okra production.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

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