

Review Paper

Cotton Whitefly (*Bemisia tabaci*) Management: An Integrated Review on Biology, Molecular Identification, and Control Technologies

Meer Sharib Salal* and Farrukh Baig

Department of Entomology, Muhammad Nawaz Shareef University of Agriculture, Multan
60000, Pakistan

*Corresponding author: meersalal2r1@gmail.com

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Abstract

Cotton is a major source of foreign exchange and rural employment in Pakistan, yet national production fell from 13.9 million bales in 2014-15 to 8.5 million bales in 2019-20. The whitefly *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) is among the most damaging biotic constraints on the crop. It injures plants by phloem feeding, contaminates leaves with honeydew that supports sooty mould, and transmits begomoviruses, including those that cause cotton leaf curl disease (CLCuD). *Bemisia tabaci* is a complex of morphologically indistinguishable cryptic species. Four of them (MEAM1, Asia I, Asia II 1 and NAFME) have been confirmed in Pakistan, and Asia II 1 is associated with high CLCuD incidence in Punjab. This review summarizes the taxonomy, biology, host range and molecular identification of the complex, and evaluates cultural, mechanical, botanical, visual, olfactory, vibrational, chemical and molecular control options. The efficacy evidence is drawn largely from laboratory bioassays and from vegetable crops, the summary statistics are rarely comparable between studies, and few studies report results by cryptic species, which limits transfer to cotton. Neonicotinoid resistance ratios of 6.5 to 66 fold have been recorded in Punjab populations, and target-site resistance to neonicotinoids has now been demonstrated. Secondary endosymbionts such as *Hamiltonella* may influence virus persistence in Asia II 1 populations, but this has not been tested in Pakistani field populations. Cryptic species identification, resistance phenotyping and endosymbiont screening should be run on the same field samples before rotation schedules and IPM recommendations for Punjab cotton are revised.

Keywords:

Bemisia tabaci;
botanical extracts;
cotton leaf curl
disease; cryptic
species;
endosymbionts;
insecticide resistance;
integrated pest
management; sensory
traps

1. Introduction

Cotton (*Gossypium hirsutum* L.) supplies the fibre for a global textile industry worth about US\$600 billion a year (Shuli et al., 2018). Pakistan is the fourth-largest cotton producer in the world (Afzal et al., 2023), and the crop earns foreign exchange that has led to its description as “white gold” (Khan et al., 2020). Output has nevertheless declined: national production fell from 13.9 million bales in 2014-15 to 8.5 million bales in 2019-20, a reduction of 39% in five years (Rana et al., 2020). Insect pests and viral diseases have been identified as the main biotic causes of this decline (Afzal et al., 2023; Shahid et al., 2022), and the most damaging of them is the whitefly *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae).

B. tabaci is a polyphagous insect that originated in southern Asia and now occurs on all inhabited continents, with the highest densities in tropical and subtropical regions (Abubakar et al., 2022). It feeds on more than 900 plant species (Perring, 2001) and damages crops in three ways. Nymphs and adults remove phloem sap, which causes wilting, chlorosis and stunted growth. Honeydew excreted during feeding supports sooty mould that reduces photosynthesis and makes produce unmarketable. The insect also transmits more than 300 plant viruses in the genera *Begomovirus*, *Carlavirus*, *Ipomovirus*, *Torradovirus* and *Crinivirus* (Jones, 2003; Khan et al., 2012; Lu et al., 2019).

Bemisia tabaci is not a single species. It is a complex of morphologically indistinguishable cryptic species that differ in host preference, begomovirus transmission efficiency, insecticide resistance profile and geographic distribution. Four members of the complex have been confirmed in Pakistan: Middle East-Asia Minor 1 (MEAM1, formerly the B biotype), Asia I, Asia II 1 and North Africa-Middle East (NAFME) (Ashfaq et al., 2014). Asia II 1 has been associated with a high incidence of cotton leaf curl disease (CLCuD) in Punjab, the centre of Pakistani cotton production (Ahmed et al., 2011). Identification of these species with the mitochondrial cytochrome oxidase I (COI) gene is therefore a practical requirement for pest management and not only a taxonomic exercise (Afzal et al., 2023; Ashfaq et al., 2014).

Synthetic insecticides, first pyrethroids and more recently neonicotinoids, have been the main control tool, but resistance has been reported in several cryptic species (Liu & Meister, 2001; Riley, 1994). Whitefly integrated pest management (IPM) therefore combines several tactics, because no single measure gives adequate or durable control. These include cultural practices such as intercropping, mulching and adjusted sowing dates, botanical insecticides such as neem extracts and green-synthesised nanoformulations, and sensory technologies such as semiochemical repellents, mating disruption and LED-based visual traps (Abubakar et al., 2022; Sani et al., 2020; Schlaeger et al., 2018; Yanagisawa et al., 2024).

This review has three aims. It summarizes the taxonomy, morphology, life history, host range and molecular identification of the *B. tabaci* complex, with reference to Pakistani cotton. It evaluates cultural, mechanical, botanical, visual, olfactory, vibrational and chemical control options, together with resistance mechanisms and the role of bacterial endosymbionts. It also appraises critically the quality and comparability of the underlying data, because much of the published efficacy evidence comes from laboratory assays and from crops other than cotton.

Biological control by natural enemies has been reviewed elsewhere (Liu et al., 2015; Sani et al., 2020) and is discussed here only where it interacts with other tactics.

1.1 Cotton in Pakistan

Cotton is the main source of foreign exchange among Pakistani crops and contributes directly to gross domestic product (GDP) (Ali et al., 2019). Agriculture accounts for about 19.2% of GDP and 39% of employment (Baig et al., 2022). About 26% of Pakistani farmers grow cotton, and the crop occupies more than 15% of the cultivated area, with production concentrated in Punjab and Sindh (Rana et al., 2020). Cotton contributes about 0.8% of GDP and 4.5% of the value added in agriculture (Rana et al., 2020).

The area sown to cotton fell by 12.1% in 2018-19, mainly because of severe disease and insect pest outbreaks (Shahid et al., 2022), and declined by a further 6.8%, from 2,079 thousand hectares in 2020-21 to about 1,937 thousand hectares in 2021-22 (Afzal et al., 2023). Annual production from 2015-16 to 2024-25 is shown in Fig. 1. Output exceeded 10 million bales only in 2017-18 and fell to 3.90 million bales in 2022-23, a season that also included catastrophic monsoon flooding.

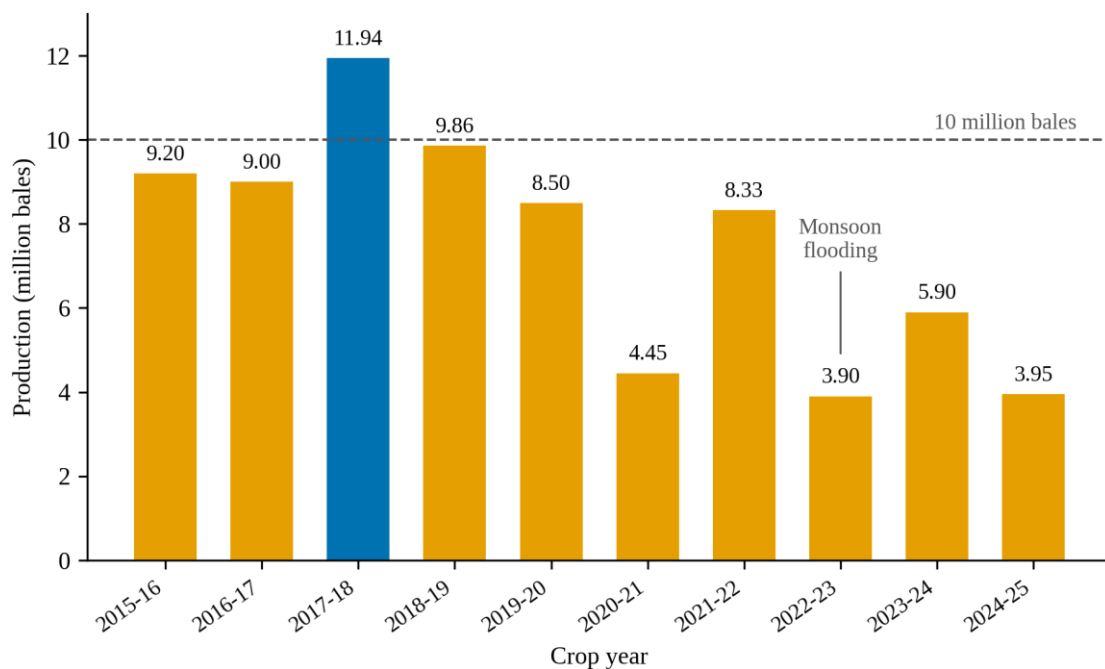


Fig. 1. Annual cotton production in Pakistan, 2015-16 to 2024-25. The dashed line marks 10 million bales, and the blue bar is the only season above it. Values were compiled from USDA FAS GAIN reports (2015 to 2025), the Pakistan Cotton Ginners Association (PCGA) and the Pakistan Bureau of Statistics (PBS). These sources define a bale differently, so the series is indicative only. The 2022-23 season also reflects catastrophic monsoon flooding.

Fig. 1 does not isolate the effect of *B. tabaci*. Production is the product of area, yield and season, and the sown area fell over the same period. Flooding, disease and other insect pests also contributed to the low output of 2022-23. Attributing the trend to the whitefly and CLCuD

therefore requires yield-loss trials or district-level surveys of vector density and disease incidence, which remain scarce for Pakistan. The series in Fig. 1 was also compiled from USDA FAS, PCGA and PBS reports, which do not define a bale in the same way (480 lb in USDA reports and 170 kg in Pakistani sources). The values should be read as indicative trends and not as a single harmonised series.

1.2 Importance of *Bemisia tabaci*

A single female *B. tabaci* can lay up to 320 eggs during her lifetime (Abubakar et al., 2022; Burnett, 1949), so populations can reach damaging densities within a few generations. Nymphs and adults both feed on phloem sap and excrete honeydew, which supports sooty mould on foliage and fruit and reduces yield. Affected plants show leaf folding, yellowing, deformed fruit and poor growth (Abubakar et al., 2022). Adults are mobile, whereas nymphs settle after a short crawling phase in the first instar and remain fixed to the leaf (Liu et al., 2015).

Bemisia tabaci is also an efficient vector of more than 300 plant viruses, including members of the genera *Carlavirus*, *Ipomovirus*, *Begomovirus*, *Torradovirus* and *Crinivirus* (Abubakar et al., 2022; Jones, 2003; Lu et al., 2019). Begomovirus infection can reduce crop yields by 20% and, in the worst cases, cause total loss, with financial damage running to millions of dollars (Sani et al., 2020). New begomovirus strains continue to emerge, which increases the risk to farmers in tropical and subtropical regions (Khan et al., 2012).

1.3 Taxonomy of whiteflies

Whiteflies comprise more than 1,550 described species, of which about 50 are agricultural pests (Liu et al., 2015). All belong to the family Aleyrodidae, which is divided into three subfamilies: Udamoselinae, Aleyrodinae and Aleurodicinae. The Aleurodicinae contains twenty genera and about 130 known species. The sources cited here record them mainly from South and Central America and the Caribbean, with some records from North Africa, the Mediterranean, the Middle East and Pakistan (Abubakar et al., 2022; Afzal et al., 2023).

Four species of Aleyrodidae have a major effect on agricultural economies: *B. tabaci*, *Aleurocanthus woglumi* Ashby, *Trialeurodes vaporariorum* (Westwood) and *Aleyrodes proletella* (Linnaeus). *Bemisia tabaci* occurs in many regions and seriously damages fruit, vegetable and ornamental crops. *Trialeurodes vaporariorum*, the greenhouse whitefly, is a pest of protected crops and develops on a wide range of hosts, chiefly in the families Solanaceae, Malvaceae, Cucurbitaceae and Asteraceae. *Aleurocanthus woglumi*, the citrus blackfly, has a greyish-blue body and occurs on more than 300 host plants, although citrus (orange, pomelo and lemon) is the most heavily infested (Afzal et al., 2023; Mound & Halsey, 1978). *Aleyrodes proletella*, the cabbage whitefly, infests plants in the families Papaveraceae, Fabaceae, Brassicaceae, Euphorbiaceae and Apiaceae (De Barro & Driver, 1997).

Estimates of the number of plant viruses transmitted by *B. tabaci* differ among the cited sources, from about 111 (Abubakar et al., 2022; Njoroge et al., 2017) to more than 300 (Jones, 2003; Lu et al., 2019). The higher figure is used in this review. Only three viruses have been reported from *Trialeurodes abutilonea* (Haldeman) and *T. vaporariorum* (Abubakar et al., 2022; Njoroge et al., 2017). *Bemisia tabaci* feeds on field crops, ornamentals and vegetables,

including okra, cotton, tomato, potato, tobacco and chilli (Afzal et al., 2025). Its mouthparts are modified into long, flexible stylets that reach the phloem (Wang et al., 2017). Direct feeding by adults and nymphs, together with virus transmission, causes considerable damage and yield loss (Abubakar et al., 2022).

Bemisia tabaci is a cryptic species complex whose members are morphologically indistinguishable but reproductively isolated. Estimates of the size of the complex differ with the delimitation method, from at least 34 species (Ashfaq et al., 2014; de Moraes et al., 2018) to 46 (Afzal et al., 2023). Members were formerly called biotypes (Abubakar et al., 2022). They are separated by molecular and biochemical markers and by traits such as host range (de Moraes et al., 2018).

1.4 Comparative biology and management differences among cryptic species

The *B. tabaci* complex is not a single pest with regional variants. It is a set of reproductively isolated species that differ in invasion history, virus vector competence and insecticide susceptibility, and treating them as interchangeable in a management context obscures differences that are operationally significant. Geographical distribution and genetic analysis indicate that Middle East-Asia Minor 1 (MEAM1) underwent a recent global invasion built almost entirely on a single mitochondrial haplotype, which accounts for nearly 80% of all invaded-range records. India is a conspicuous exception, because MEAM1 never spread beyond the south of the country despite arriving at roughly the same time as in Australia, China and the United States (Peng et al., 2025).

Within China, two invasive cryptic species, MEAM1 and Mediterranean (MED), arrived about a decade apart and then competed for the same niche. Population genetic analysis of 22 MED and 8 MEAM1 populations found that MED carries substantially greater genetic diversity on both mitochondrial and microsatellite markers, which the authors link to the subsequent displacement of MEAM1 as the dominant field population (Xue et al., 2024). This pattern is relevant to Pakistani IPM planning. A cryptic species that cannot be told apart from one already under control can displace it within a few growing seasons if it carries a fitness or diversity advantage, and a resistance management plan calibrated to one species may be obsolete before the displacement is detected in routine monitoring.

Insecticide susceptibility differs sharply between cryptic species that occupy the same cropping system. Naveen et al. (2017) screened Asia I, Asia II 1 and Asia II 7 populations from Indian cotton-growing tracts and reported susceptibility differences exceeding 100,000-fold across the three groups for some compounds. Asia I and Asia II 1 were consistently the least susceptible. Resistance ratios for cypermethrin, monocrotophos, triazophos, imidacloprid and thiamethoxam in Asia I ranged from three- to sevenfold above susceptible baselines, and Asia II 1 carried six- to sevenfold resistance to cypermethrin and deltamethrin. A rotation schedule designed against one genetic group will not hold against a field population shifting towards another. This is the situation already documented for Punjab cotton, where Asia II 1 and NAFME mitotypes now co-occur with MEAM1 and Asia I (Shah et al., 2020).

Vector competence for begomoviruses separates by cryptic species and not by the complex as a whole. Transmission assays for cotton leaf curl Multan virus found that Asia II 7

transmitted the virus to two of three tested cotton cultivars at efficiencies of 30 to 40%, whereas MEAM1 and MED failed to transmit it to any of the same cultivars under identical conditions (Farooq et al., 2022). The mechanism involves species-specific suppression of whitefly antiviral immunity by the viral coat protein, so vector competence depends on molecular interactions that differ between whitefly lineages and not only on feeding behaviour. In Pakistan, Asia II 1 is already associated with CLCuD incidence in Punjab (Ahmed et al., 2011). Whether co-occurring NAFME and Asia I populations in the same districts carry a comparable or lower risk of CLCuD transmission has not been tested directly in Pakistani field populations.

Haplotype-level structure within a single cryptic species can also carry epidemiological weight. Within the NAFME group, phylogeographic and SNP analysis of the B mitotype identified eight haplotypes, of which only two have established outside their endemic zone of origin, while the remaining six stayed confined to their ancestral niches despite decades of opportunity for spread through trade (Paredes-Montero et al., 2021). In Oman, native and introduced NAFME haplotypes differ in the begomoviruses with which they associate, with haplotype 5 linked to an endemic virus and haplotype 2 linked to an introduced one (Shahid et al., 2023). NAFME has expanded from Sindh into Punjab (Shah et al., 2020), and haplotype-level resolution may be needed before the role of NAFME in Pakistani CLCuD epidemiology can be assessed. Most of the contrasts in this section rest on one or two studies each. They show that differences between cryptic species exist, but they do not fix the size of those differences for Pakistani field populations.

1.5 Background of whitefly in Pakistan

Ashfaq et al. (2014) used COI barcoding to identify the members of the complex present in Pakistan. Asia I occurred in both Sindh and Punjab, Asia II 1 occurred in Punjab, and MEAM1 was restricted to Sindh. NAFME was first found only in Sindh and has since spread into Punjab (Shah et al., 2020). Asia II 1 has been linked with higher CLCuD incidence in Punjab (Ahmed et al., 2011), and CLCuD causes a marked reduction in productivity. Populations of *B. tabaci* have been recorded in Multan, Dera Ghazi Khan and Rajanpur (Abbas et al., 2023), and mitotype surveys have covered Khanewal, Muzaffargarh, Vehari, Lodhran and Bahawalpur (Shah et al., 2020).

The COI gene is the marker most widely used to identify these cryptic species, and a complete COI barcode provides a reliable and cost-effective basis for identification (Afzal et al., 2023). Because COI is a single maternally inherited locus, it identifies mitochondrial lineages and not reproductive units, and haplotype-level resolution adds information that species-level barcodes cannot provide (Paredes-Montero et al., 2021).

1.6 Morphology

Whitefly identification relies on the fourth-instar nymph, commonly called the puparium. The adults of *Trialeurodes ricini* and *Bemisia afer* have not been adequately described (Malumphy et al., 2009). Hill (1969) described all developmental stages of *B. tabaci* and *T. vaporariorum* reared on tobacco under laboratory conditions in South Africa.

Adult *B. tabaci* are pale yellow with two pairs of unmarked white wings that are lightly coated with fine waxy powder, as in *T. vaporariorum*. At rest, the wings of *B. tabaci* are

narrower and more sharply pointed towards the posterior end than those of *T. vaporariorum*. The anterior margin of the forewing is straight in *B. tabaci* and curved in *T. vaporariorum*. Adult *B. tabaci* are also smaller and a darker yellow than adult *T. vaporariorum*. The antenna of *B. tabaci* has seven segments, with pit sensoria on the third, fifth, sixth and seventh segments and stout sensory setae on the third and seventh (Patel et al., 2022). Mellor and Anderson (1995) described the antennal sensilla of *T. vaporariorum* and *A. proletella*.

The compound eye of adult *B. tabaci* is divided, and each half contains two clusters of lenses joined by a single connecting lens. The mesothoracic tibiae carry stout spines arranged at random. In females, the ventral side of the abdomen bears two pairs of wax plates on the third and fourth segments, whereas males have four pairs on the third to sixth segments. The supragenital plate is weakly developed in females. In males it is modified into a tube-like collar at the tip of the abdomen, around the distal part of the genitalia (Patel et al., 2022).

1.7 Life cycle of *Bemisia tabaci*

Females begin to oviposit after mating (Ghelani et al., 2020). The eggs are pear-shaped and about 0.2 mm long, and they are laid on the leaf surface, often in a semicircular pattern. They are pearly white at first and darken over several days, and the distal end turns dark brown just before hatching (Abubakar et al., 2022; Ghelani et al., 2020). Eggs hatch into first-instar nymphs after 5 to 9 days, depending on host variety, moisture and temperature (Ghelani et al., 2020).

The first instar, called the crawler, is whitish yellow and oval, flat and scale-like. The second instar is dome-shaped and yellowish. The third instar is bright yellow after moulting, then darkens progressively and appears slightly constricted (Abubakar et al., 2022). The fourth instar is yellow and white with prominent red eyes that show through the integument, and is also called the pupal or red-eyed nymph (Perring et al., 2018). Nymphs are flat and resemble the adult, but they are immobile and periodically produce filaments of wax (Abubakar et al., 2022; Rodríguez et al., 2019).

The adult emerges through a T-shaped slit in the dorsal surface of the pupal case. The abdomen is rounded and larger in females and pointed in males (Abubakar et al., 2022; Fekrat & Shishehbor, 2007; Perring et al., 2018). The complete life cycle takes about 16 to 31 days (Abubakar et al., 2022; Fekrat & Shishehbor, 2007; Lindquist, 1998). Adults of the Q biotype live longer than those of the B biotype, but the Q biotype completes its life cycle more quickly (Sani et al., 2020). The wide range of 16 to 31 days reflects differences in temperature, host plant and biotype, and development times for the cryptic species present in Pakistan should be measured at field temperature regimes so that degree-day models can be parameterised (Fig. 2).

1.8 Host plants

Bemisia tabaci attacks many host species, including the crops cotton (Shukla et al., 2016), tomato (Baldin et al., 2015), muskmelon (Lot et al., 1982), sunflower (Qiu et al., 2007), tobacco (Javaid et al., 2016), okra (Rehman et al., 2020), potato and lettuce (Cabanillas & Jones, 2009) and cucumber (Ansari et al., 2020). Soybean, eggplant, cabbage, cucurbits, black pepper and groundnut are also hosts (Abubakar et al., 2022). In Pakistan, 229 host species have

been recorded, comprising fruit plants, weeds, field crops, ornamentals, vegetables and forest trees (Afzal et al., 2023). Across its range, the insect is reported from about 900 plant species (Perring, 2001), and *G. hirsutum* is the host of greatest economic importance among them.

Host plant affects development differently among cryptic species. Asia I developed faster on cotton than on vegetables, whereas development of NAFME did not differ significantly among hosts. Whitefly densities were higher on food and fibre crops than on horticultural crops in samples taken from ornamental and vegetable plants (Afzal et al., 2023). Table 1 summarizes published effects of whitefly infestation on different crops.

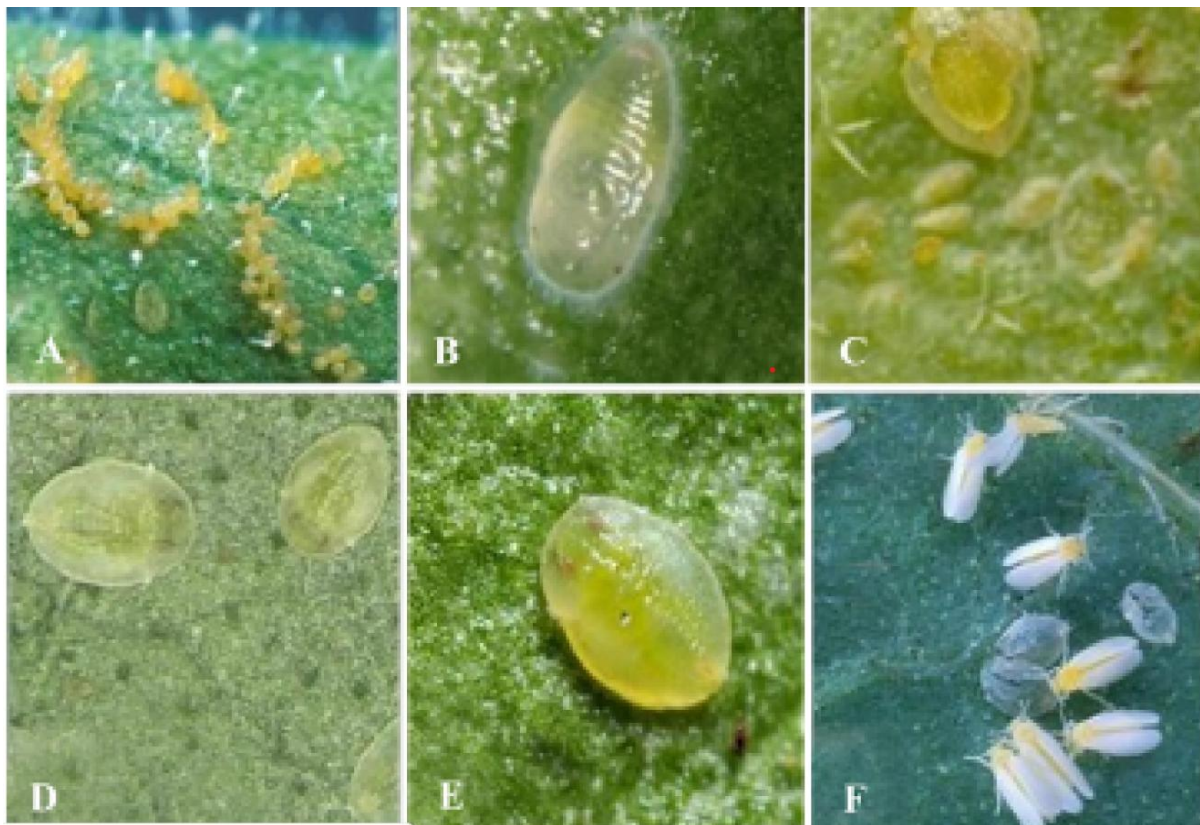


Fig. 2. Life cycle of *Bemisia tabaci*. (A) Eggs attached to the leaf by a stalk-like pedicel; (B) first-instar nymph; (C) second-, third- and fourth-instar nymphs; (D) fourth-instar nymph with red eyes; (E) pharate adult; (F) adults after emergence, with transparent exuviae. Reproduced from (Abubakar et al., 2022), published under a CC BY 4.0 licence.

The 21 entries in Table 1 cannot be pooled or ranked. They use incompatible response variables, including monetary loss, percentage yield loss, pigment content, gas exchange, seed mass and symptom descriptions, and they cover more than a dozen crops grown under conditions that range from controlled experiments to commercial fields. Five of the 21 entries concern tomato. Some entries describe direct feeding damage (the chlorophyll reductions in tobacco, eggplant and tomato), while others describe outcomes driven by virus transmission (potato in India and chilli in Sri Lanka). The tobacco data show that damage increases with infestation time, with chlorophyll a reductions of 42.36%, 56.96% and 81.43% at days 11, 14

and 20, but whitefly density and exposure period differed between studies. Cotton, the focal crop of this review, has no entry in Table 1. The effect of *B. tabaci* on cotton yield must therefore be inferred from disease-loss ranges (Fig. 3) and production statistics (Fig. 1) and not from measured infestation-yield relationships. Field studies that establish economic thresholds for Pakistani cotton would fill this gap.

Table 1. Reported effects of *Bemisia tabaci* infestation on different crops.

Crop	Location	Reported effect
Tomato	Florida, USA	Financial losses exceeded US\$125 million.
Tomato	Israel	Leaves curled, flowers dropped prematurely, internodes shortened, growth stunted and leaf texture hardened.
Tomato	Spain	Several necrotic rings formed on leaf surfaces.
Tomato	Spain	In winter trials, 0.23 ± 0.10 perforations per leaf and 0.3 ± 0.12 per fruit; summer trials gave a similar pattern.
Tomato	Egypt	Chlorophyll a fell by 8% and chlorophyll b by 12.8% in infested leaves.
Eggplant	China	Plant height fell by 12.6%, leaf area by 12.7%, biomass by 8.2%, absolute growth rate by 26.0%, relative growth rate by 25.0% and assimilation efficiency by 22.2%.
Eggplant	China	Leaf area fell by 26.6%, fresh mass by 21.8% and dry mass by 19.27%; pigment content and photosynthetic light processing fell by 9.7% and 65.9%, respectively.
Tobacco	China	Chlorophyll a in infested leaves was 42.36%, 56.96% and 81.43% lower than in healthy plants at days 11, 14 and 20.
Sugarcane	Iran	Pigment content fell to 0.583 mg g^{-1} , compared with 1.48 mg g^{-1} in uninfested plants.
Cantaloupe, cucumber, zucchini	Saudi Arabia	Mean pigment content was 0.87 (cantaloupe), 1.12 (cucumber) and 0.54 (zucchini), against control values of 1.13, 2.09 and 1.05.
Zucchini	Florida, USA	Leaf petioles lost 66% of their pigment content relative to leaf blades early in the infestation.
Zucchini	Florida, USA	Fruit production fell as pest numbers rose: control 5.1 ± 0.5 , 30 pairs 3.9 ± 0.5 , 60 pairs 0.4 ± 0.1 and 120 pairs 0.
Cassava	Fiji	Gas exchange fell to $11.90 \text{ mmol m}^{-2} \text{ s}^{-1}$ from $17.80 \text{ mmol m}^{-2} \text{ s}^{-1}$ in pest-free leaves.
Soybean	Brazil	Seed mass fell to 33 g per thousand grains, and protein production losses reached 440 kg ha^{-1} .
Snap bean	Georgia, USA	Harvest losses reached 45%.
Squash	Georgia, USA	Crop losses reached 35%.
Vegetables	Texas, USA	Economic damage totalled US\$29 million.
Vegetables	South Carolina, USA	Leaves became swollen, misshapen, rolled and wrinkled.

Crop	Location	Reported effect
Potato	India	Virus infection rates transmitted by the pest ranged from 40% to 75%.
Coconut palm	India	Heavy infestations covered about 60% of the leaf area and caused yellowing, tissue death and water loss.
Chilli	Sri Lanka	Virus-induced leaf curl disease twisted foliage and inhibited plant growth.

Source: compiled from (Abubakar et al., 2022). Entries are as reported in the original studies and use different response variables.

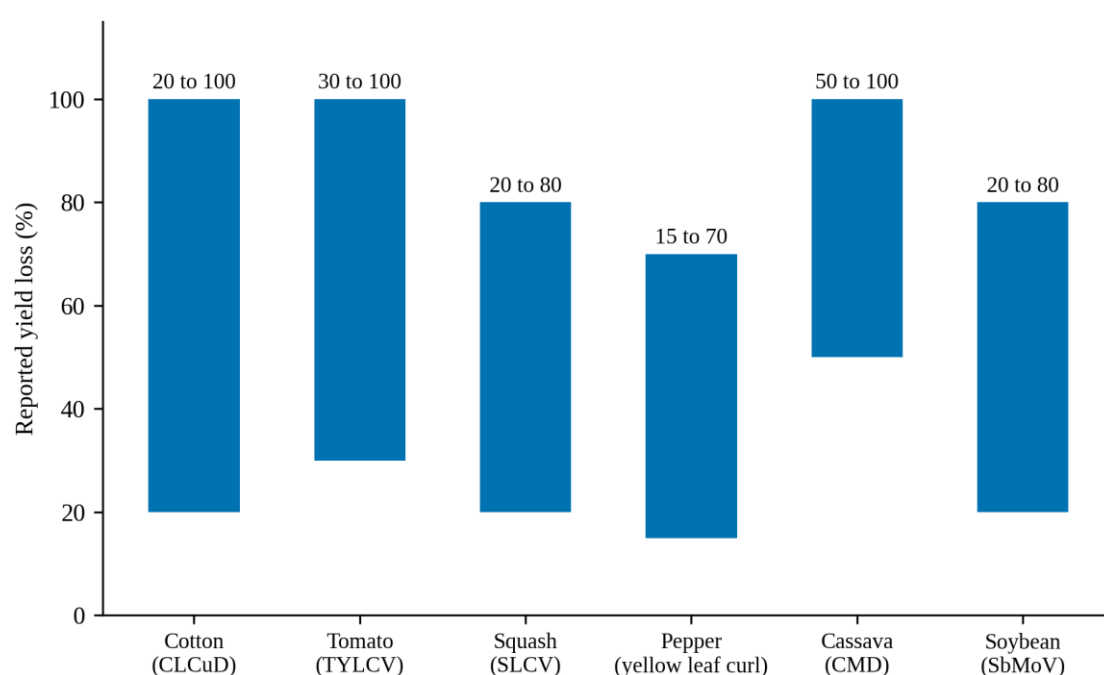


Fig. 3. Reported yield losses (%) in major crops attributed to whitefly-transmitted begomoviruses. Bars span the minimum to the maximum reported value. CLCuD, cotton leaf curl disease; TYLCV, tomato yellow leaf curl virus; SLCV, squash leaf curl virus; CMD, cassava mosaic disease; SbMoV, define this virus as in the source. Values were compiled from (Sani et al., 2020), (Khan et al., 2012) and (Lapidot et al., 2014).

The ranges in Fig. 3 are wide, for example 20 to 100% for CLCuD in cotton and 30 to 100% for tomato yellow leaf curl virus in tomato, because they combine cultivars, growth stages at infection, virus strains and seasons, and because the upper limits usually describe epidemic seasons in unprotected fields. They express potential loss and not expected loss, and they are unsuitable for calculating economic thresholds. The ranges were also taken from secondary reviews (Khan et al., 2012; Lapidot et al., 2014; Sani et al., 2020), and future analyses should use primary loss assessments for CLCuD in Pakistani cotton cultivars under current management.

2. Management strategies for whitefly

Whitefly management draws on physical and mechanical methods such as traps and barriers (Dent & Binks, 2020; Perring et al., 2018), plant-derived products (Cloyd et al., 2009), indigenous technical knowledge (ITK) (Abubakar et al., 2022), biotechnological approaches (Ibrahim et al., 2017), biological control (Liu et al., 2015; Sani et al., 2020), synthetic insecticides (Abubakar et al., 2022; Liu & Meister, 2001; Riley, 1994) and IPM programmes that combine these tactics (Abubakar et al., 2022). Fig. 4 gives an overview of these strategies.

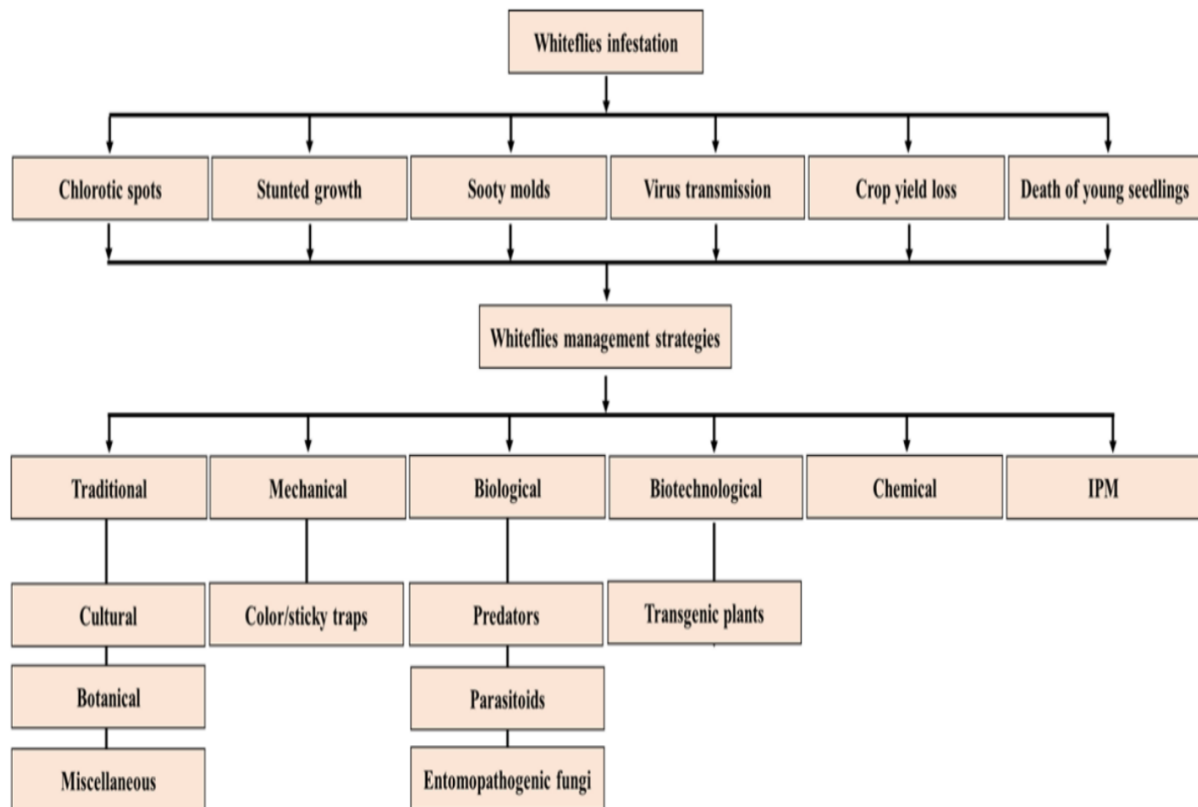


Fig. 4. Overview of whitefly management strategies. Reproduced from (Abubakar et al., 2022), published under a CC BY 4.0 licence.

Fig. 4 arranges the tactics discussed below in six steps: pest detection and species identification, cultural and physical control, biological control, botanical and biorational control, chemical control as a last resort with rotation of insecticide classes, and emerging technologies. The framework is a conceptual synthesis of the cited reviews and has not been validated in field trials, so it should be treated as a planning aid and not as a tested decision rule.

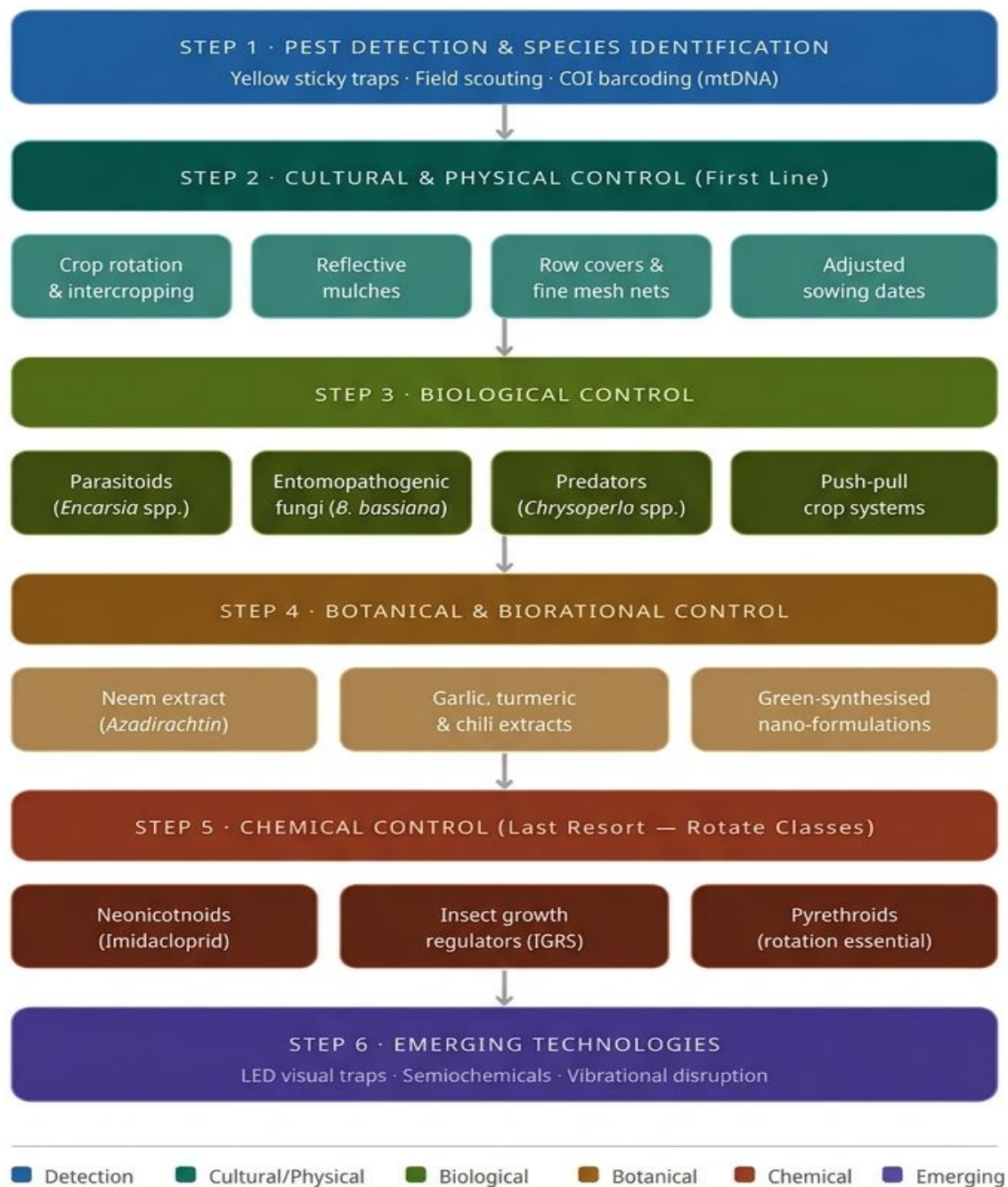


Fig. 5. Stepwise IPM decision framework for *B. tabaci*, from detection and species identification to emerging technologies. Adapted from (Abubakar et al., 2022), (Sani et al., 2020) and (Yanagisawa et al., 2024). The framework is a conceptual synthesis and has not been validated in field trials.

2.1 Physical and cultural strategies

Cultural techniques such as fertilizer use and irrigation practice can make crop fields less favourable to insect pests (Lapidot et al., 2014; Perring et al., 2018). In several crops, drip irrigation lowered whitefly populations and virus transmission compared with furrow irrigation. Sprinkler irrigation reduced whitefly populations and associated viruses in tomato when the crop was interplanted with coriander. Adjusting the sowing date allows vulnerable

host plants to avoid the peak of whitefly abundance (Abd-Rabou & Simmons, 2012; Mohamed, 2012; Togni et al., 2018).

Both organic mulches (compost, cocoa hulls, wheat straw, wood and bark chips) and synthetic mulches (plastic sheeting and rubber chips) are effective against *B. tabaci* on vegetables. Aluminium-coated plastic mulch and organic mulches suppress viral pathogens and insect pests in tomato, snap bean, squash and melon, and silver mulch reflects sunlight and repels whiteflies. Barrier and trap crops interfere with host location by the insect and have controlled virus spread in several crops. Squash and brinjal planted around snap bean and tomato protected those crops from whitefly (Abubakar et al., 2022). Intercropping ginger or coriander with okra reduced whitefly numbers on okra, and intercropping cucumber with lettuce reduced them by 69.7% (Asawalam & Chukwu, 2012; Zhongxia et al., 2004). Sprinkler irrigation combined with intercropping made tomato plants less susceptible to colonisation by *B. tabaci* (Hilje et al., 2001).

Farmers are reluctant to adopt living barriers, trap crops, mulches, higher planting density and floating row covers because these techniques require major changes to traditional cropping systems. In recent years, however, some farmers have adopted crop timing that places the crop in a host-free period, together with fine-mesh barriers and other exclusion methods (Hilje et al., 2001). The evidence reviewed above comes almost entirely from vegetables, mostly from small plots, and the effects reported are single-study values, such as the 69.7% reduction with cucumber and lettuce. The studies cited do not show that mulching or trap cropping is practicable on broadacre cotton.

2.2 Indigenous technical knowledge and other conventional practices

Farmers spray sour buttermilk on plants to deter sap-feeding pests. Milk contains casein, spreads well and adheres to whitefly wings, which is believed to kill the insects (Abubakar et al., 2022). Fermented cow milk sprayed on okra reduced whitefly numbers, and a mixture with chilli extract made the plants less suitable for the insect (Elango et al., 2020). Buttermilk combined with detergents thinned out winged pests on black gram (Taggar & Singh, 2020).

Cattle urine is also sprayed on crops. It may reduce plant disease and promote growth, and some farmers use it against whiteflies on various crops, sometimes with higher yields. A mixture of 10% cow urine and 1% starch, sometimes combined with chlorantraniliprole 18.5% SC, keeps pests off vegetables. Herbs soaked in cow urine kill whiteflies but spare the natural enemies that feed on them. *Vitex trifolia* L. and *Lantana camara* L. blended with cow urine had strong effects on the aphid *Lipaphis erysimi* (Kaltenbach) (Abubakar et al., 2022). A mixture of cow dung, urine, ash, slurry or vermiwash lowered whitefly numbers on eggplant (Karkar, 2014). Chilli, garlic and neem leaves soaked in cow urine reduced whitefly on okra and also suppressed some other insects (Singh et al., 2021). A mixture of kerosene, water and soap works as a contact insecticide against sucking pests, but kerosene applied to tomato reduced whitefly numbers and also lowered yield (Abubakar et al., 2022; Oparaeké et al., 2003). Table 2 lists the conventional practices reported for whitefly management.

Table 2. Conventional and traditional practices used against *Bemisia tabaci*, with reported effects.

Crop	Material and application	Reported effect	Category
Tomato	Yellow sticky traps placed 1.4 m above ground in the centre of the greenhouse.	A maximum of 67 whiteflies per trap.	Physical trap
Tomato	Yellow sticky traps hung vertically or parallel to the crop rows.	Vertical traps caught more whiteflies, averaging 66.57 per row in the field.	Physical trap
Tomato	Adhesive traps of different colours and shapes at densities of 2, 4 and 6 traps per 250 m ² .	Yellow rectangular traps were most effective, averaging 5.7 whiteflies per trap.	Physical trap
Eggplant	Yellow sticky traps placed 30 cm above the plants at one trap per 5 m ² in the field.	Up to 27 whiteflies caught in six days.	Physical trap
Brinjal	Wood ash at 50 g per plant; cow urine, cow dung, slurry and water sprayed at 1:10 on five consecutive days.	Lower pest density and production cost, with minimal adverse effects on non-target arthropods.	Organic / ITK
Eggplant	Cow urine and vermiwash at 20, 30, 40 and 50%, applied separately.	Whitefly numbers fell significantly; 50% was most effective.	Organic / ITK
Brinjal	Cow urine at 20 to 50% combined with plant extracts and vermiwash.	Lowest mean count (2.22 per plant) with 20% cow urine plus 10% neem leaf extract.	Organic / ITK
Cotton	Non-sticky, yellow sticky and colourless sticky cards of 72 and 93.75 cm ² , assessed after 24 h.	Non-sticky cards caught 264 whiteflies, yellow sticky cards 523 and colourless sticky cards 37 per card.	Physical trap
Pepper	Yellow sticky traps and trap crops, alone and combined, in the field.	Yellow sticky traps alone were most effective, averaging 42 whiteflies per trap.	Physical trap; trap crop
Cotton	Yellow sticky traps hung vertically 45 cm above the canopy on wooden poles.	Mean catch of 34.07 whiteflies per trap; leaf populations fell to 0.83 whiteflies per leaf.	Physical trap
Okra	Ten litres of buttermilk fermented; 1 L diluted in 9 L of water and sprayed.	Total whitefly population fell by 60%.	Organic / ITK
Crop plants (general)	Hot chilli pod filtrate and marigold diluted 1:2 with water; 1 teaspoon of soap added per litre before spraying.	Most common agricultural pests were curtailed or controlled.	Plant extract / soap

Crop	Material and application	Reported effect	Category
Cowpea	Cow urine at 25, 50, 75 and 100%, each with 1% neem seed kernel extract.	100% cow urine plus 1% neem was most effective, leaving 13.26 whiteflies per leaf.	Organic / ITK
Okra	Mixture of pepper, garlic, neem leaf and cow urine applied at 10% w/v.	Whitefly population fell by 95.2%, among the highest efficacies reported.	Organic / ITK
Crop plants (general)	20 g of crushed turmeric root steeped in 200 mL of cattle urine, diluted in 2 to 3 L of water, with soap (8 to 12 mL per application).	Whiteflies, aphids, caterpillars and red mites were significantly suppressed.	Organic / ITK
Agricultural crops (general)	Cow urine diluted 1:20 in water.	Effective against insect pests and pathogens; also acted as a foliar fertiliser.	Organic / ITK
Crop plants (general)	Fermented curd water (buttermilk) sprayed as an ITK practice.	Whiteflies, jassids, aphids and similar pests were suppressed.	Organic / ITK
Agricultural crops (general)	Cow dung and urine combined with fermented plant extracts, 1:20 in water.	Several insect pests were controlled across crops.	Organic / ITK
Okra	Improvised coloured traps: 1,500 mL plastic bottles painted purple, yellow, black or green, placed 2 m apart and 0.6 m above the canopy.	Yellow traps were most effective, averaging 61.13 whiteflies per trap.	Physical trap
Crop plants (general)	Kerosene, soap and water emulsion sprayed on crops.	The emulsion damaged sucking insects, including whiteflies.	Organic / ITK
Cotton	Perimeter intercropping with trap or barrier crops and parasitoids; three intercrop programmes and three peripheral planting arrangements.	About 1.44 nymphs and 1.15 adults per 100 cm ² of leaf, indicating moderate suppression.	Biological / intercropping
Black gram	Buttermilk, Lisapol detergent, soap, Indo-neem, Actara and neem, applied singly and in mixtures in the field.	Treated plants averaged 7.56 whiteflies per leaf against 37.11 in untreated controls; mixtures reduced numbers by 26.50 to 27.35%.	Plant extract / soap

Source: compiled from (Abubakar et al., 2022).

Trap catches illustrate the difficulty of comparing results across studies. Yellow sticky traps captured a mean of 5.7 to 67 whiteflies per trap, depending on crop, trap height, density and exposure period (six days in eggplant and 24 h in the cotton card comparison), so the counts are not interchangeable. In the cotton comparison, yellow sticky cards caught 523 whiteflies,

non-sticky cards 264 and colourless sticky cards 37 after 24 h, which shows that both colour and adhesive affect catch. Catch is a measure of attraction and not of population suppression. As summarized in Table 2, only one trap entry (cotton) reports leaf-level populations, and none reports yield or virus incidence.

Most ITK entries in Table 2 lack a quantified effect or a comparison with a chemical standard, and the reported outcomes range from a 95.2% reduction (pepper, garlic, neem and cow urine on okra) to a residual density of 13.26 whiteflies per leaf (cowpea), which are different metrics. Concentrations, preparation methods and application intervals also differ, and no entry reports phytotoxicity, residues or the mechanism of action. The kerosene emulsion lowered tomato yield, which shows that a lower pest count does not guarantee an agronomic benefit. These practices are best regarded as hypotheses for controlled field testing on cotton and not as recommendations.

2.3 Plant-based extracts

Many plant-derived products are active against *B. tabaci*. A foliar spray of crushed turmeric root in cow urine controlled whitefly, powdery mildew and other insects (Abubakar et al., 2022; Ravindran et al., 2007). A hexane extract of neem (*Azadirachta indica* A. Juss) was active against adult *B. tabaci* (Castillo-Sánchez et al., 2015), and aqueous extracts of neem and *Jatropha curcas* L. were tested against *B. tabaci* and *Helicoverpa armigera* (Hübner) on tomato in Côte d'Ivoire (Diabaté et al., 2014). Plant-derived essential oils had lethal and inhibitory effects on *B. tabaci* biotype B on tomato (Fanela et al., 2016). Chilli and marigold extracts performed better than others against most insects, and leaf extracts were effective against hemipterans. A formulation made from *Vitex negundo* L. leaves is applied against whitefly and several other pests (Abubakar et al., 2022; Pesticide Action Network Germany [PAN Germany], 2008). *Adenocalymma alliaceum* and *Piper callosum* Ruiz & Pav. prevent *B. tabaci* from settling and ovipositing on tomato (Abubakar et al., 2022).

Patchouli oil repelled up to 85% of whiteflies in choice and no-choice tests and reduced oviposition by 50 to 89%. Neem treatment reduced oviposition by about 50%, nymph populations by 70% and adult emergence by about 80% relative to untreated plants (Amour et al., 2023). Plant-derived oils are widely used against *B. tabaci* (Baldin et al., 2015). Table 3 summarizes the effects of botanicals on different crops.

Table 3. Effects of botanical treatments on *Bemisia tabaci* in different crops and test systems.

Crop or test system	Botanical treatment	Reported outcome
Sweet potato	Petunia-derived compounds	70% adult mortality and 82% egg mortality at 0.5 and 1 mg mL ⁻¹ .
Tomato, cucumber, bean	Water, methanol and acetone extracts of chinaberry fruit and leaves	The methanol extract lowered pest density to 1.44 ± 0.24 individuals per plant.
Tomato	Leaf and seed extracts of eight plant species	<i>Jatropha dhofarica</i> L. gave the highest mortality (41%) and <i>Azadirachta indica</i> A. Juss the lowest (30.85%).

Crop or test system	Botanical treatment	Reported outcome
Tomato	Ginger oils	The oils deterred colonisation of tomato plants.
Melon	Essential oils of thyme and peppermint	Peppermint was 62.78% effective, and thyme eliminated the pest completely.
Tomato	Seed extracts of <i>Trichilia havanensis</i> Jacq. and <i>Passiflora edulis</i> Sims	<i>P. edulis</i> caused 60% mortality and <i>T. havanensis</i> 70%.
Not specified	Crude and partially purified saponins from fruit of <i>Sapindus saponaria</i> L.	Mortality rose with saponin concentration, from 20% to 80%.
Soybean, cotton, melon	Sugar apple oil formulations	Immature stages shrivelled and detached from the leaf surface after oil exposure.
Coleus	Essential oils of several plant species	No tested oil gave adequate control after one, two or three weeks.
Sweet potato	Aqueous plant extracts	Lethal potency was comparable to that of imidacloprid.
Laboratory	Mint and colothyn leaf preparations (crude or formulated)	Reported 100% mortality of both whitefly and aphid at the median lethal concentration.
Dry bean	Neem oils	By day 6, mortality of first- to third-instar nymphs exceeded 80% at 1% concentration.
Laboratory	Essential oils of four plant species	Maximum mortality of 79%.
Sweet potato	Neem-based botanical pesticides	Oviposition fell by 23.1%, egg viability by 53.2% and adult emergence by 26.6% relative to untreated controls.
Okra	Neem oil formulations	5% neem oil caused 70.77% mortality within 72 h.
Various crops	Essential oils	The oils acted as repellents, insecticides and developmental inhibitors.
Tomato	Fermented mixtures of marigold, neem, makabuhay and kakawate	The marigold formulation was more effective than the other three.
Laboratory	Secondary compounds from citronella grass, cumin, lemongrass and cinnamon, and essential oils	Cinnamaldehyde was repellent at 0.084 mg L ⁻¹ and lethal at 8.4 mg L ⁻¹ ; linalool was inhibitory at 0.006 mg L ⁻¹ , with no lethal dose determined.
Y-tube olfactometer	Volatiles from six plant species	Responses included over 80% attraction, over 62% repellence and over 80% oviposition deterrence.

Crop or test system	Botanical treatment	Reported outcome
Not specified	Leaf preparations of <i>Eugenia</i> sp.	Mortality ranged from 80% to 97%.
Okra	Various plant-derived compounds	Populations fell by 5.19% to 63.17%.
Tomato	Essential oils of bitter orange and clove	Mortality ranged from 70% to 90%.
Tomato	Essential oils of several plant species	Adults fell to 6.6 ± 0.93 and eggs to 6.0 ± 2.39 , against 22.6 ± 2.23 and 70.6 ± 19.29 in controls.
Potato	Extracts of pomegranate, liquorice, turmeric, thyme and neem	Neem oil was most potent, reducing pest density by 66.79% and 67.71% in the 2014 and 2015 seasons.
Tomato	Aqueous plant preparations	Egg mortality of 78% and adult mortality of 72.8%.
Laboratory	Essential oils of cumin, cinnamon and lemongrass	After 1 day, cinnamaldehyde gave 100% toxicity, geraniol 32.1% and citronellol 17.1%.
Laboratory	Essential oils from four principal chemical components and <i>Gardenia jasminoides</i> Ellis	Vapour-phase activity against adults of 81.48% and direct toxicity to immature stages of 77.28%.
Eggplant	Aqueous extracts of nine plant species	Cottonseed extract performed best against field infestations.
Chilli	Aqueous botanical extracts	Mortality of immature stages reached 96.67%.
Cucumber	Plant-derived compounds and commercial insecticides	Pest elimination approached 80%.
Cotton	Essential oils of four plant species	Mortality ranged from 30.8% to 64.2%.
Cowpea	Neem leaf preparations	Populations of whiteflies, aphids and pod-boring insects fell (no values given).
Diet bioassays	Aqueous and methanol extracts of French marigold	Oviposition suppression and mortality both reached 80%.
Common bean	Nano-encapsulated essential oils from fruit and leaves of <i>Xylopia aromatica</i> (Lam.) Mart.	Oviposition on snap bean leaves fell by 98%.
Various plants	Lemon peel essential oil	Mortality of 99% to 100% for both whitefly and mealybug.
Strawberry, tomato	Chamomile preparations and neem oils	Neem oil caused 60% to 71.3% mortality, chamomile and lechuguilla extracts 62%, and neem oil with cactus pectin 60%.

Crop or test system	Botanical treatment	Reported outcome
Cotton	Volatiles of <i>Ocimum gratissimum</i> L. and <i>Cymbopogon citratus</i> Stapf	The lower <i>C. citratus</i> concentration reduced counts to 3.77 ± 0.51 per 30 plants, and 5% <i>O. gratissimum</i> to 3.38 ± 0.53 per 30 plants.
Laboratory	Avocado kernel extract	Mortality of 90% in adults and 98.3% in nymphs.
Tomato	Ethanol extracts of <i>Annona</i> species	Within 13 days of LC ₉₀ treatment, egg hatch fell to 35.00% compared with the other groups.

Source: compiled from (Abubakar et al., 2022).

Reported effects in Table 3 range from a 5.19% population reduction (okra) to complete mortality, but the entries differ in test system (leaf dip, Y-tube olfactometer, vapour-phase assay and field spray), life stage assessed, exposure time and concentration units (percentage, mg mL⁻¹, mg L⁻¹, LC₅₀ and LC₉₀). Only three entries report a measure of variability. Some entries are internally inconsistent as reported, for example 100% mortality at a stated median lethal concentration, and the primary papers should be consulted before such values are used in analyses. Two entries in the source compilation that did not describe botanical treatments were omitted from Table 3, and two entries that appeared to describe the same neem study were merged.

Laboratory results that approach complete mortality (thyme, lemon peel and cinnamaldehyde) do not predict field performance. Essential oils are volatile, so residual activity on a crop canopy may be short, and no entry in Table 3 reports persistence or phytotoxicity. Efficacy is also inconsistent: none of the coleus oils gave adequate control after one to three weeks, and four essential oils reached only 30.8 to 64.2% mortality on cotton. Cotton appears in only three entries (sugar apple oil, four essential oils, and *Ocimum gratissimum* L. and *Cymbopogon citratus* Stapf volatiles). Fig. 6 plots selected values from the literature. The studies behind the bars used different methods, so the figure shows the range of reported outcomes and does not rank the botanicals.

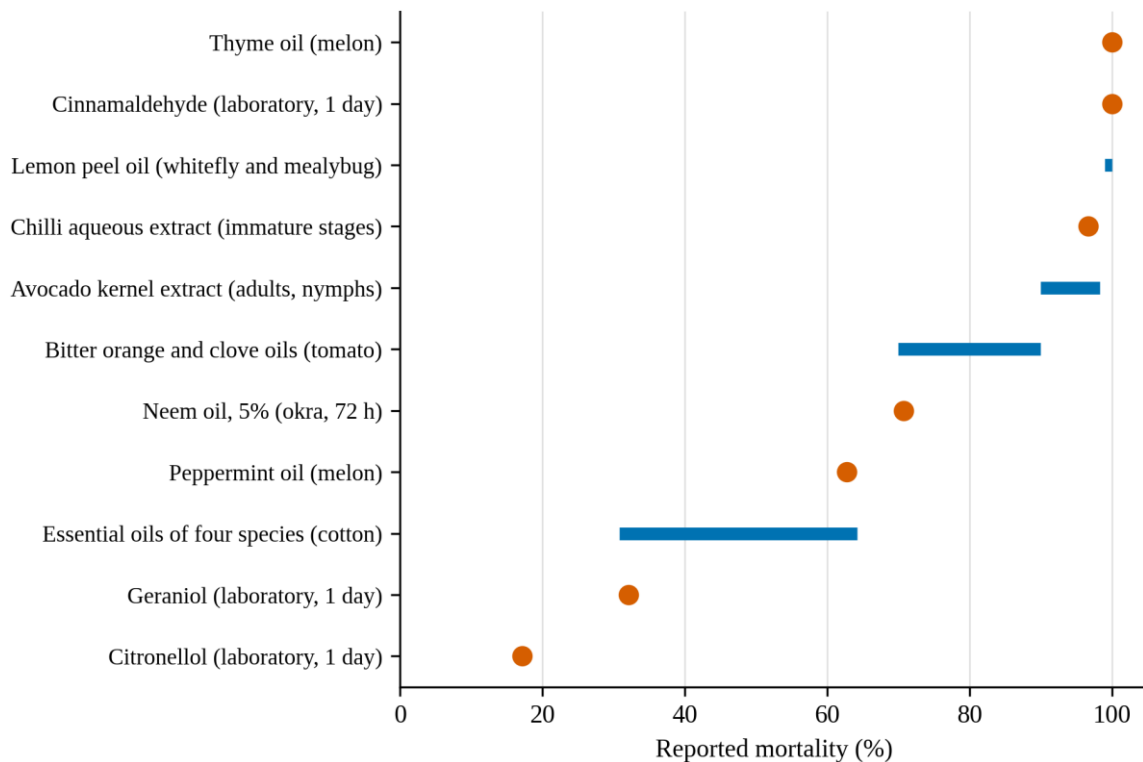


Fig. 6. Mortality (%) of *B. tabaci* reported for selected botanical treatments listed in Table 3. Points are single reported values and bars are reported ranges. The values come from different test systems, life stages, exposure times and concentrations, so they are not directly comparable, and no measure of variability is available.

2.4 Mechanical strategies

Mechanical methods place a physical obstacle between the pest and the host plant. Fifty-mesh screens on greenhouse side walls keep whiteflies out and limit the spread of tomato yellow leaf curl virus (TYLCV) in tomato, and a UV-absorbing layer can greatly improve screen performance (Abubakar et al., 2022; Legarrea et al., 2010). Polypropylene covers controlled whitefly populations and reduced the rate of TYLCV spread among tomato plants (Cohen & Berlinger, 1986). Zucchini grown under Agryl fabric in low tunnels was protected from infestation and from squash leaf curl virus (SLCV), a begomovirus, even when whitefly populations were at their peak (Abubakar et al., 2022). Sticky traps also serve as a sampling tool. Saady (2022) used them to collect adult whiteflies directly from leaves into bioassay containers without anaesthesia or aspiration. All of these studies concern tomato, zucchini or other protected crops, so barriers are relevant to nurseries and greenhouse production more than to open-field cotton.

2.5 Visual control

Mass trapping with green or yellow LED traps stimulates long-wavelength-sensitive (LWS) photoreceptors more strongly than short-wavelength-sensitive (SWS) photoreceptors, which increases the catch of *T. vaporariorum* and related pests (Roberts et al., 2025; Stukenberg et al., 2015). Light can also be used as a repellent (push). Blue and blue-UV LEDs

aimed at the underside of leaves disturb *T. vaporariorum* and repelled over 87% of the whitefly population, and repellency increased with light intensity and exposure duration (Athanasiadou & Meyhöfer, 2024). UV or blue light may disturb beneficial insects and natural enemies, so LED settings should be adjusted to avoid harming them (Athanasiadou et al., 2024). UV-reflective foils and mulches, especially white materials that reflect wavelengths between 400 and 490 nm, can keep whiteflies from landing on crop plants. This probably occurs because the reflected light alters how the crop appears to the insect and keeps it in continued flight (Athanasiadou & Meyhöfer, 2024). Almost all of the LED data cited here concern *T. vaporariorum* in glasshouses. Field evidence for *B. tabaci* on open cotton is not available in the sources reviewed, so the effect sizes above cannot be transferred directly.

2.6 Olfactory control

Repellent plants and volatiles can reduce settlement of *B. tabaci* on a focal crop in some systems. Examples are intercropping with plants that emit repellent volatile organic compounds (VOCs) and the use of repellent oils such as ginger oil and coriander-based mixtures (Feres et al., 2016; Mrisho et al., 2021; Schlaeger et al., 2018). Attract-and-kill strategies use host volatiles to draw whiteflies to trap crops, and masking the target crop with other VOCs is a developing alternative (Mrisho et al., 2021; Schlaeger et al., 2018). Molecular olfaction targets such as the odorant receptor co-receptor (Orco) and chemosensory proteins are candidates for RNA interference (RNAi) or behaviour-modifying compounds (Li et al., 2024a; Schlaeger et al., 2018).

Choice experiments with *B. tabaci* show that yellow visual cues and plant volatiles act additively or synergistically in host selection. Visual and olfactory stimuli from TYLCV-symptomatic tomato plants together produced the strongest attraction (Johnston & Martini, 2020). Infection of tomato with tomato severe rugose virus (ToSRV) or tomato chlorosis virus (ToCV) increases whitefly landing on infected plants through visual cues, whereas olfactory cues favour healthy plants. Vectors are therefore drawn first to infected plants and then to healthy ones, which promotes virus spread (Feres et al., 2016; Ontiveros et al., 2022). This finding shows that olfactory tactics can influence virus spread in ways that a count of whiteflies will not reveal, so they should be evaluated against virus incidence as well as vector density. The olfactory evidence cited here comes from tomato and cassava in olfactometer or small-cage tests, and none of it concerns cotton.

2.7 Vibrational control

A recent review concludes that vibration-based pest management is promising for whiteflies and other pests, with the potential to reduce pesticide use and increase yield when integrated into greenhouse infrastructure (Yanagisawa et al., 2024). Laboratory work shows that artificial vibrations of 200 to 1,500 Hz at amplitudes of about 1 μm can disrupt the mating behaviour of *B. tabaci* and greatly reduce successful copulation (Ebihara, 2019). Vibrational actuators installed on greenhouse structures or trellis wires could jam mating signals and reduce whitefly reproduction without chemicals (Fattoruso et al., 2021; Yanagisawa et al., 2024). The evidence is limited to laboratory mating assays and to work on the greenhouse whitefly *T. vaporariorum*, and no field data for *B. tabaci* in cotton were found in the sources reviewed.

The approach is at the research stage. Fig. 7 summarizes the mechanical, visual, olfactory and vibrational strategies.

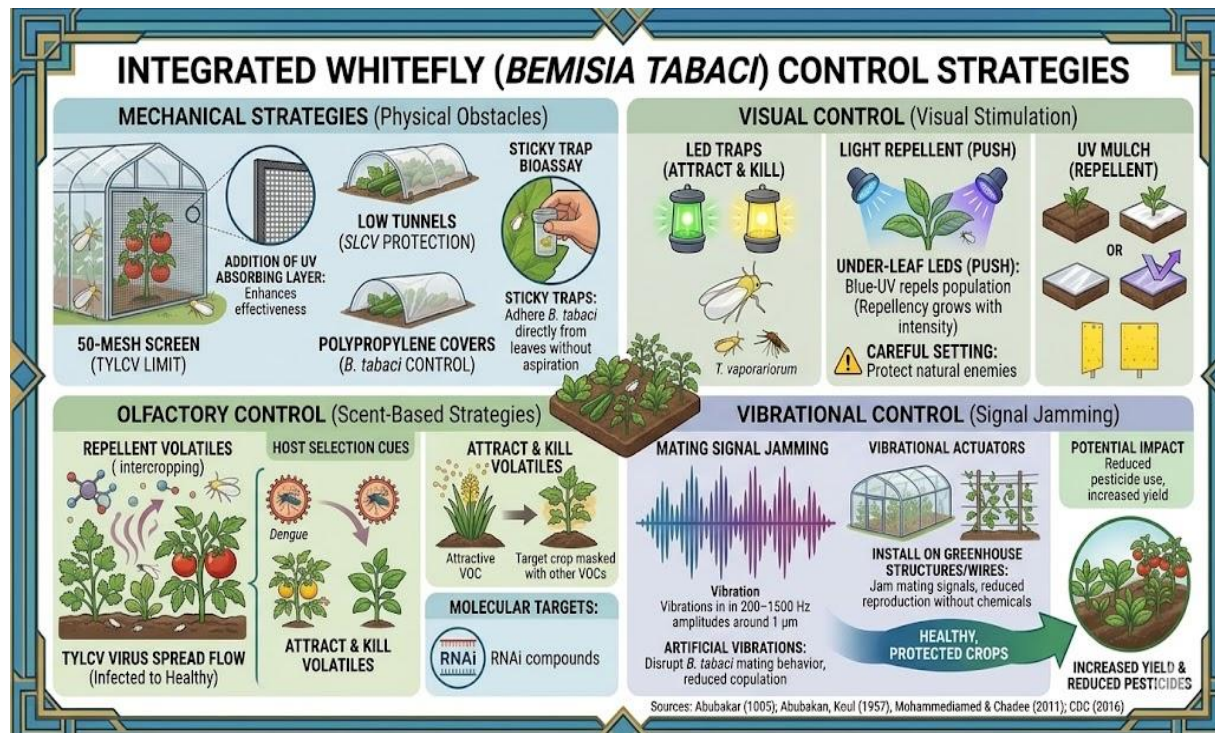


Fig. 7. Mechanical, visual, olfactory and vibrational control strategies for *B. tabaci*. Conceptual illustration based on Abubakar et al. (2022) and the sources cited in Sections 2.4 to 2.7. ChatGPT was used to create this figure.

2.8 Insecticide resistance and chemical control of *Bemisia tabaci*

Chemical insecticides have been, and remain, the main means of controlling *B. tabaci* in field and protected cropping systems. The classes used over the years include carbamates, organophosphates and pyrethroids, which act at different neural sites, and more recently the neonicotinoids. Decades of intensive, calendar-based application have reduced the efficacy of almost every class. Documented resistance in *B. tabaci* covers cyclodienes, organophosphates, carbamates and pyrethroids, with resistance ratios from 7 to more than 2,000 fold (Naveen et al., 2019; Palumbo et al., 2001). Resistance to the neonicotinoid imidacloprid and to the insect growth regulator (IGR) buprofezin has reached particularly high levels in field populations worldwide (Kranthi et al., 2024; Naveen et al., 2019). Once resistance is established, whitefly populations are difficult to keep below threshold, so early detection and proactive management are needed.

Cryptic species structure complicates the picture. As described in Section 1.4, susceptibility varied by more than 100,000-fold between cryptic species in Indian cotton-growing areas, and Asia I and Asia II 1 were the least susceptible groups whereas Asia II 7 was the most susceptible (Naveen et al., 2017). The resistance data for Asia I and Asia II 1 indicate a risk of control failure in the field with pyrethroids, monocrotophos and triazophos. In

Pakistan, early work documented resistance to organophosphate and pyrethroid insecticides (Ahmad et al., 2002). Resistance monitoring in Punjab has since recorded moderate to high neonicotinoid resistance in Bahawalpur, Faisalabad, Lodhran, Multan and Vehari, with resistance ratios for acetamiprid, imidacloprid, thiamethoxam and thiacloprid of about 6.5 to 66 fold (Aslam et al., 2022). Whitefly resistance is therefore an established problem in Pakistani fields and not a theoretical one.

Two biochemical mechanisms contribute to resistance in *B. tabaci*: metabolic detoxification and target-site modification. Metabolic resistance mainly involves upregulation of cytochrome P450 monooxygenases (CYPs), glutathione S-transferases (GSTs) and carboxylesterases. The P450 gene *CYP6CM1* is consistently overexpressed in neonicotinoid-resistant populations, and an amino acid substitution (A387G) in some *CYP6CM1* alleles markedly increases the ability of the enzyme to metabolise imidacloprid and thiamethoxam (Pym et al., 2023). Other P450 genes, including *CYP6DW3*, *CYP4CS5* and *CYP306A1*, have been shown to contribute to neonicotinoid detoxification. *CYP306A1* confers resistance to imidacloprid in nymphs by lowering the in vivo insecticide concentration by about 20% (Feng et al., 2023; Guo et al., 2023; Zhang et al., 2023). GSTs are also important. The enzyme BtGSTz1 metabolised 36.36% of the available imidacloprid in resistant populations, and silencing it by RNAi significantly increased mortality in bioassays (Li et al., 2024b). In resistant populations from Türkiye, monooxygenase, GST and non-specific esterase activities were significantly higher than in susceptible reference strains (Ozkan et al., 2024). Metabolic resistance in *B. tabaci* is rarely the product of one gene. It is a layered detoxification system that degrades insecticides faster than they can reach their molecular targets.

Target-site resistance operates independently of metabolic mechanisms and often adds to them. For pyrethroids, mutations in the voltage-gated sodium channel (L925I and T929V) confer knockdown resistance (*kdr*) and have been detected at high frequencies in field populations in China, Australia and Greece (Chen et al., 2020; Herron et al., 2022; Mavridis et al., 2022). In Australian MEAM1 populations, the organophosphate resistance allele F331W in acetylcholinesterase 1 (*ace1*) was at or near fixation in all sampled fields, which effectively removes the organophosphate and carbamate classes from whitefly management in that cropping system (Herron et al., 2022). Target-site resistance to neonicotinoids was long considered absent from *B. tabaci*. This position was overturned by the identification of two mutations (A58T and R79E) in the nicotinic acetylcholine receptor $\beta 1$ subunit (*BT β 1*). When the mutations were expressed in transgenic *Drosophila melanogaster* Meigen, they conferred resistance by electrostatically repelling neonicotinoids at the orthosteric binding site, and the resistance extended to several neonicotinoid compounds (Yin et al., 2024). Neonicotinoids have been the main rescue chemistry for decades, so this finding has direct consequences for whitefly management (Fig. 8).

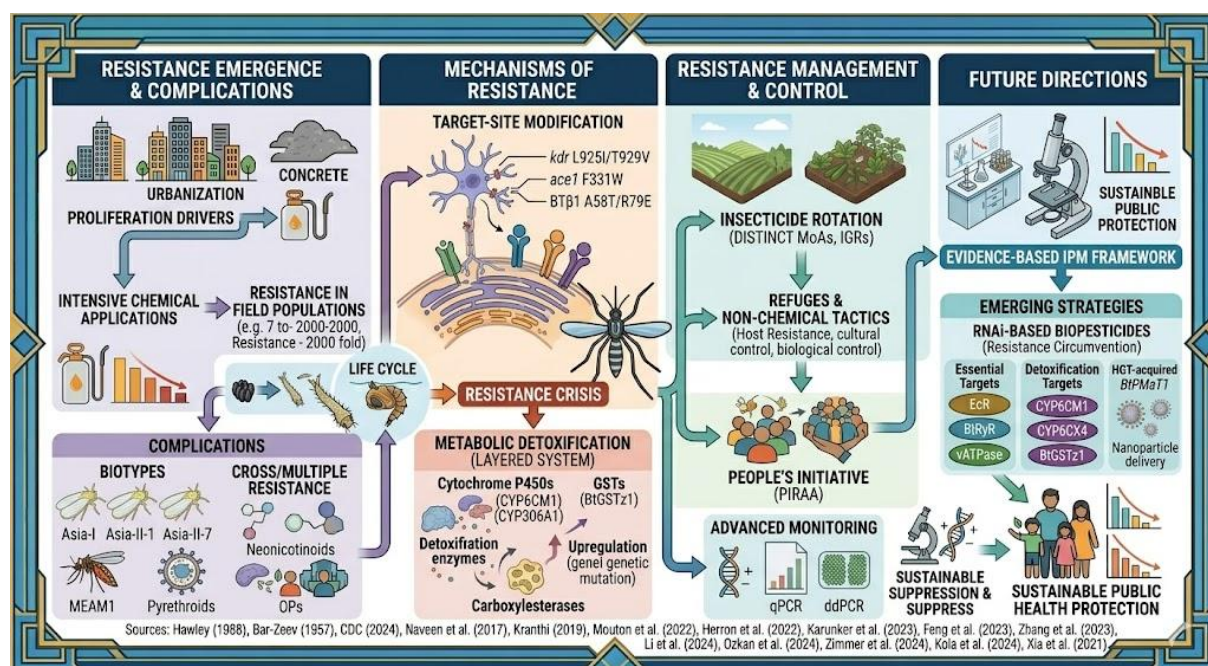


Fig. 8. Emergence, mechanisms and management of insecticide resistance in *B. tabaci*. Conceptual illustration based on the sources cited in Section 2.8. ChatGPT was used to create this figure.

Cross-resistance and multiple resistance have also been observed. Field populations of *B. tabaci* MED (Q biotype) in Türkiye were simultaneously highly resistant to imidacloprid (303 fold), acetamiprid (282 fold), chlorpyrifos-ethyl (53 fold) and deltamethrin (76 fold), and both metabolic and target-site mechanisms contributed (Ozkan et al., 2024). Populations selected experimentally for imidacloprid resistance showed reduced susceptibility to thiamethoxam and acetamiprid because of P450-mediated detoxification. In contrast, sulfoxaflor showed no cross-resistance with neonicotinoids in Q-biotype strains from eastern China. Flupyradifurone-resistant strains were moderately cross-resistant to imidacloprid but not to cyantraniliprole (Guo et al., 2020; Pan et al., 2017). This information can be used to design rotation sequences.

Resistance management therefore depends on a diverse set of tactics supported by sound data, and not on a single insecticide group. From a chemical control perspective, the most practical way to delay resistance is to rotate insecticides with different modes of action. Adding IGRs such as pyriproxyfen and buprofezin to rotation sequences can preserve susceptibility to key compounds if they are applied so as to protect natural enemies early in the crop cycle. Refuges, meaning parts of the crop that are not exposed to insecticide selection, have been proposed as a way to maintain susceptible individuals and dilute resistance allele frequencies over time. Non-chemical tactics, including host plant resistance, cultural control and biological control agents, reduce reliance on insecticides and lower selection pressure. Molecular tools now inform these decisions more precisely. TaqMan qPCR and droplet digital PCR (ddPCR) allow the frequencies of specific resistance alleles, including F331W (*ace1*), L925I and T929V (sodium channel) and A2083V (acetyl-CoA carboxylase), to be monitored in individual insects with a limit of detection below 0.2% (Mavridis et al., 2022). Combined

with phenotypic bioassays, these tools give a more complete picture of resistance status than bioassays alone and allow intervention before resistance reaches damaging frequencies.

Most of the resistance data above come from India, China, Türkiye and Australia. For Pakistan, the evidence is limited to an early study (Ahmad et al., 2002) and one recent district survey (Aslam et al., 2022) that, as the Conclusion explains, was not stratified by cryptic species. Resistance ratios are also calculated against different susceptible reference strains, so comparisons across studies are qualitative. For example, the 6.5 to 66 fold ratios in Punjab and the 303-fold ratio for imidacloprid in Türkiye cannot be ranked without a common baseline.

RNAi-based biopesticides are a promising option for species-specific management that circumvents existing resistance. Silencing targets include the essential genes for the ecdysone receptor (*EcR*), ryanodine receptor (*BtRyR*), vacuolar ATPase (*V-ATPase*) and the nAChR $\beta 1$ subunit (*BtnAChR- $\beta 1$*). Delivery of double-stranded RNA by chitosan nanoparticles or nanoclay carriers produced more than 80% mortality under laboratory conditions and substantially reduced fecundity (Kola et al., 2024; Nameirakpam et al., 2025). Silencing detoxification genes such as *CYP6CM1*, *CYP6CX4* and *BtGSTz1* could counteract existing resistance by removing the mechanisms that allow *B. tabaci* to withstand insecticides, and it may restore the efficacy of current insecticide classes. Another gene of interest, *BtPMT1*, was transferred horizontally from plants to *B. tabaci* and allows the whitefly to malonylate phenolic glucosides and thereby inactivate them. Silencing *BtPMT1* with small interfering RNAs prevented whiteflies from detoxifying plant secondary metabolites when they were reared on tomato, which shows that horizontally transferred genes can be exploited as molecular targets (Xia et al., 2021). Sustainable use of RNAi requires a species-specific, life-history-based and population-genetic approach to limit off-target effects and the evolution of resistance to RNAi itself (Shelby et al., 2020). The mortality figures above were obtained in the laboratory, and field delivery, cost and regulatory status remain untested. Combining RNAi biopesticides with biological control, habitat manipulation and insecticide use guided by resistance monitoring is the approach most likely to be sustainable (Upadhyay et al., 2020).

2.9 Bacterial endosymbionts of *B. tabaci* and their relevance to Pakistani pest management

Every individual in the *B. tabaci* complex carries the obligate primary endosymbiont *Portiera aleyrodidarum*, which supplies essential amino acids that are absent from the phloem diet. It has been found in all cryptic species and geographic populations sampled to date (Hashmi et al., 2018). A variable community of facultative secondary endosymbionts, principally *Hamiltonella*, *Rickettsia*, *Arsenophonus*, *Cardinium* and *Wolbachia*, is added to this universal primary symbiosis, and its presence and frequency differ by cryptic species, host plant and geographic region (Hashmi et al., 2018).

The first comprehensive survey of secondary endosymbionts in Pakistani field populations found *Hamiltonella* to be the most prevalent secondary symbiont overall. It occurred in 68% of Asia II 1 individuals, 100% of Asia I individuals and 21% of MEAM1 individuals, and its highest regional prevalence, 80%, was recorded in Punjab (Masood et al., 2026). *Hamiltonella* has been implicated in protecting begomoviruses within the insect vector and may contribute to virus persistence and onward transmission and not act as a neutral

passenger (Masood et al., 2026). The same study found a strong negative association between *Hamiltonella* and certain co-occurring symbionts, which suggests competitive exclusion within the host and not free co-infection. Because *Hamiltonella* was more prevalent in Asia I (100%) than in Asia II 1 (68%), its prevalence alone does not explain the association of Asia II 1 with CLCuD. Any contribution of the symbiont to virus transmission is correlational at present and must be tested by transmission assays.

Endosymbiont titre responds to abiotic stress in ways that bear on whitefly persistence under Pakistani summer field conditions. In Asia I populations exposed to experimental heat and cold shock, secondary symbiont titres declined significantly after heat treatment, whereas the titre of the primary symbiont *Portiera* remained comparatively stable, and expression of the heat-shock proteins Hsp40 and Hsp70 increased under both stresses (Barman et al., 2023). Thermal stress from climate variability or exposed-row cultivation may therefore shift the secondary symbiont community in ways that alter resistance phenotype or virus transmission capacity, independently of any change in insecticide exposure.

Secondary endosymbiont screening can be added to existing COI-based cryptic species identification protocols at low marginal cost, because both rely on PCR from the same insect template. Running cryptic species identification and endosymbiont screening on the same field-collected samples, and not as parallel unlinked programmes, would allow resistance risk and virus transmission risk to be assessed together. This is a question of study design and not of laboratory capacity.

3. Conclusion

Bemisia tabaci management in Pakistani cotton cannot be designed around the species complex as a single unit. Cryptic species identity predicts insecticide susceptibility differences exceeding 100,000-fold in some comparisons (Naveen et al., 2017), predicts which lineages transmit CLCuD efficiently (Ahmed et al., 2011; Farooq et al., 2022), and now appears to predict which secondary endosymbiont community a population carries, with consequences for virus persistence that have only recently been documented in Pakistani populations (Masood et al., 2026). A management programme built on whitefly counts alone, without cryptic species and symbiont resolution, leaves most of the relevant biological information unused.

The evidence base for control tactics is uneven. Cultural, botanical, visual, olfactory and vibrational tactics have mostly been tested in vegetables, greenhouses and laboratory assays. Cotton appears in few entries, effects are reported in incompatible units, measures of variability are seldom given, and cryptic species identity is rarely stated. Future trials on cotton should report the cryptic species tested, include untreated controls, measure yield and virus incidence as well as whitefly counts, and use standard units for efficacy.

Three gaps can be addressed with existing Pakistani research infrastructure. First, haplotype-level resolution already applied to NAFME populations in Oman has not been extended to Pakistani NAFME populations, despite the documented expansion of NAFME from Sindh into Punjab. This is a direct extension of COI barcoding work already under way in the country. Second, no published study has tested whether the *Hamiltonella* prevalence pattern documented in Pakistani Asia II 1 populations correlates with field-measured CLCuD

transmission rates in the same populations. This requires pairing the existing symbiont screening protocol with transmission bioassays. Third, resistance monitoring in Punjab has been conducted at the population level without consistent cryptic species stratification, so published resistance ratios for Bahawalpur, Faisalabad, Lodhran, Multan and Vehari (Aslam et al., 2022) cannot be attributed to a specific genetic group, which weakens their value for rotation scheduling.

Closing these gaps does not require new technology. It requires running cryptic species identification, secondary endosymbiont screening and resistance phenotyping on the same field-collected samples. Sensing technologies such as UAV-based hyperspectral surveillance and AI-assisted trap image analysis are approaching field readiness and could map whitefly pressure in real time, but they will remain blunt instruments unless the genetic identity of the monitored populations is also resolved. The next productive phase of *B. tabaci* research in Pakistan is a study-design problem, and the country's existing entomological capacity is equipped to address it.

4. Declarations

Use of AI tools. The authors used Claude (Anthropic; Sonnet 5 and Sonnet 5.5 and ChatGPT) to assist with document structuring, grammatical correction and improvement of language, and to draft revised passages in response to reviewer comments. The authors checked the scientific content, the interpretation of the cited studies and the citations against the original sources, and they take full responsibility for the content and for any remaining errors.

Software used for figures. Figures 2 and 4 are reproduced from Abubakar et al. (2022), which was published under a Creative Commons Attribution (CC BY 4.0) licence. Figures 1, 3 and 6 are data charts that were redrawn in Python 3 using Matplotlib (v. 3.10.8) from the values given in the text and in Table 3. Figure 5 was drawn using ChatGPT 5. Figures 7 and 8 are conceptual illustrations that were created using ChatGPT 5. The authors reviewed the content of every figure for scientific accuracy.

Competing interests. The authors declare no conflict of interest.

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