



REVIEW ARTICLE

An in-depth study of the exotic whiteflies in India's coconut ecosystems: A bibliometric analysis and approaches to their management

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Abstract

Coconut trees are constantly threatened by various insect pests, with invasive whiteflies proving particularly harmful. Species such as the rugose spiralling whitefly (*Aleurodicus rugioperculatus*), Bondar's nesting whitefly (*Paraleyrodes bondari*), nesting whitefly (*Paraleyrodes minei*) and palm infesting whitefly (*Aleurotrachelus atratus*) are severely impacting coconut production in tropical and subtropical regions. These whiteflies damage palms by feeding on sap, disrupting nutrient flow and causing yellowing leaves and premature leaf drop. This weakens the palms, making them more vulnerable to diseases. The honeydew they produce encourages the growth of sooty mould, which blocks sunlight and further hampers photosynthesis. These whiteflies are identifiable by their waxy secretions and distinctive spiralling egg-laying patterns. Their ability to affect various hosts, including ornamental plants and crops, complicates control efforts, facilitating their spread. Natural predators, such as parasitoid wasps from the *Encarsia* and *Eretmocerus* genera, help control whitefly populations by targeting eggs and nymphs. Sustainable pest management relies on an integrated pest management (IPM) approach, which combines biological control, regular monitoring, cultural practices like pruning and sanitation and the careful use of chemical insecticides. Adopting a robust IPM strategy is key to controlling whitefly infestations, reducing pest resurgence and ensuring coconut palms' long-term health and productivity while maintaining ecosystem balance and sustainability. A bibliometric analysis using the Bibliometrix R package and VOS viewer (version 1.6.20) has been conducted to assess research trends and identify knowledge gaps.

Keywords: bibliometric analysis; distribution; host plants; invasive whiteflies; management; natural enemies; species validation; symptoms and damage

Introduction

Coconut (*Cocos nucifera* L.), often referred to as the "tree of heaven" or "kalpavriksha," is a vital plantation crop cultivated predominantly in tropical and subtropical regions. Coconuts are nutritionally rich, providing essential minerals, vitamin B, copper, iron, proteins and antioxidants. Coconut water is increasingly popular as a natural functional drink, often marketed as a "sports beverage" due to its hydrating properties (1). Additionally, virgin coconut oil is highly valued as cooking oil, recognized for its medium-chain triglycerides and beneficial antimicrobial and hypolipidemic properties.

Coconuts are grown on approximately 12.26 million hectares worldwide, yielding around 6.67 billion nuts annually, with a productivity rate of 5440 nuts per hectare. The Philippines, Indonesia and India lead in global coconut cultivation, with India growing coconuts on 2.28 million

hectares and producing over 20.5 billion nuts annually, achieving a productivity rate of 9,018 nuts/ha (2). Within India, Kerala, Karnataka and Tamil Nadu are the top three states for coconut cultivation (3).

547 insect and mite pests were recorded in coconut palms throughout the year, including 118 exotic species (4). In India, 440 whiteflies from 63 genera species have been identified, indicating a widespread threat to coconut cultivation (5).

Among these pests, the rugose spiralling whitefly (*A. rugioperculatus*), first reported in Belize in 2004, has emerged as a major concern for coconut growers in South India. This pest was identified in several regions, including Kerala and Karnataka, between 2016 and 2019 (6-8). The adults lay creamy golden eggs in a distinctive spiral pattern on the undersides of coconut leaves. Upon hatching, the nymphs feed on plant sap,

excreting honeydew that promotes the growth of sooty mold, particularly capnodium, which creates a visible charcoal-black coating on the leaves (9, 10). This fungal growth significantly impairs photosynthesis, leading to decreased yield and nut quality. A survey conducted across Tamil Nadu revealed that the damage caused by *A. rugioperculatus* varied between 40.96 % and 62.86 %, highlighting the urgent need for effective management strategies to protect coconut plantations from this invasive pest (11).

In addition to the rugose spiralling whitefly Bondar's nesting whitefly (*P. bondari*) has emerged as a significant pest in coconut plantations, first reported in Kayamkulam, Kerala, in 2018. This pest has been documented to feed on over 25 host plants posing a serious threat to coconut gardens, particularly in Tamil Nadu (12). The nymphs and adults of *P. bondari* create distinctive nesting chambers made of woolly wax on the undersides of leaflets, where they remain for egg-laying. Another invasive species, the nesting whitefly *P. minei*, was observed in coconut gardens across the Western Ghat coastal regions of Kerala and Karnataka starting in November 2018 (13). This further underscores the growing challenges posed by whitefly infestations in these regions. Additionally, the palm-infesting whitefly, *A. atratus*, was initially reported on ornamental areca palms in Karnataka's Mysore and Mandya districts 2019 (14).

Several natural enemies have been reported to help control whitefly populations. The parasitoid *Encarsia guadeloupae* has been commonly associated with the rugose spiralling whitefly (*A. rugioperculatus*) (7). Additionally, nine different predator species, including coccinellids, chrysopids, cybocephalids and formicids, have been documented preying on *A. rugioperculatus* (15). However, no native parasitoids have been identified against Bondar's nesting whitefly (*Paraleyrodes bondari*) (16). Observations of predators such as coccinellids, psocids and chrysopids on the invasive *P. minei* highlight the potential for biological control (13). Establishing these natural enemies and microbial biocontrol agents like *Isaria fumosorosea* are effective in controlling whiteflies by infecting and killing them in coconut gardens, which could favour the bio-suppression of whiteflies. While numerous insecticides are commercially available for whitefly control, their indiscriminate use can cause multiple issues. These include insect resistance, pest resurgence, secondary pest outbreaks, disruption of natural enemy complexes, biodiversity loss and environmental pollution (17). Moreover, applying insecticides to the undersides of tall fronds is logistically challenging. In response, the Government of India and ICAR declared a 'pesticide holiday' for coconut whiteflies, shifting focus toward evaluating the efficacy of potential biocontrol agents.

This article examines invasive whiteflies' occurrence, distribution and impact on coconut, covering symptoms, damage and population dynamics. It discusses species identification through morphological and molecular methods, host plants and natural enemies. Effective management strategies are also highlighted, including biological, cultural and chemical control. By emphasizing integrated pest management approaches, the goal is to mitigate the impact of these invasive whitefly species on coconut cultivation while promoting sustainable agricultural practices.

Occurrence and distribution

Rugose spiralling whitefly, *Aleurodicus rugioperculatus*

The rugose spiralling whitefly is a significant exotic pest that has severely impacted coconut-growing regions in India. Initially identified by Martin in Belize in 2004, it spread to other parts of Central and North America, including Mexico, Guatemala and Florida, where it caused damage to various plants, including gumbo limbo trees and coconut fronds (18, 19).

In India, the whitefly was first documented in Tamil Nadu in July-August 2016, in Pollachi, Coimbatore district (7). Its presence was soon reported in the coastal areas of Andhra Pradesh by late 2016 (20). A comprehensive review highlighted its widespread distribution across states such as Karnataka, Kerala, Tamil Nadu, Maharashtra, Gujarat, Himachal Pradesh and Sikkim, noting heavy infestations and the resulting secondary sooty mold infections affecting both coconut palms and surrounding horticultural crops (21). The pest continued to spread, with reports documenting significant infestations in Mandouri, West Bengal, in June 2019, marking its first appearance in that region (22). By 2020, reports also emerged of *A. rugioperculatus* in the Saurashtra region of Gujarat, further underscoring its increasing threat to coconut cultivation across India (23). Bondar's nesting whitefly, *Paraleyrodes bondari* was first described in 1971 by Peracchi, on citrus species in Brazil. As a native of the Neotropical region, this pest has since expanded its range and has been reported in several locations, including Belize, Honduras, Puerto Rico, Madeira, Comoros, Mauritius, Taiwan, Hawaii and Florida (USA) (19). In Florida, *P. bondari* was first recorded in 2011 when specimens were collected from a ficus hedge in Lee County. This marked the species' identification outside its native range. In 2018, a study reported a severe outbreak of *Paraleyrodes bondari* on cassava in Uganda (24). In India, *P. bondari* was first reported in 2019, explicitly infesting coconut trees in Kerala (25). Following this, researchers provided the first evidence of the species' invasion and establishment in the Andaman and Nicobar Islands (16).

In Tamil Nadu, the whitefly was identified in coconut plantations in Namakkal District, with previously reported findings (26). Their research noted that *P. bondari* was not limited to coconut; it was also found on a variety of other crops, including bhendi (*Abelmoschus esculentus*), chillies (*Capsicum annuum*), white poplar (*Populus alba*), banana (*Musa* spp.), guava (*Psidium guajava*) and the ornamental plant *Duranta erecta* in Coimbatore.

Nesting whitefly, *Paraleyrodes minei*

Paraleyrodes minei was first described in 1989 on *Citrus aurantium* leaves collected from the coastal region of Syria. *Paraleyrodes minei* (nesting whitefly) in Syria, despite being native to the Neotropical region, is likely due to human-mediated introduction, mainly through the international trade of live plants (EPPO global database). It was reported in California in 1984, first noticed near San Diego and the southern coast. Over the years, *P. minei* has been documented in various locations, including Belize, Guatemala, Mexico, Puerto Rico, Bermuda, Texas, Lebanon, Morocco, Spain, Turkey and Benin (27). Research highlighted the invasive nature of *P. minei* as it spread to regions like Hong Kong and Hainan (28). The pest has shown a significant global spread, reaching the

Western Palaearctic region, including countries like Iran, Israel and Turkey. It was first reported in Greece in June 2015 on sweet orange leaves in Platani, Chania (29).

In the Andaman and Nicobar Islands of India, *P. minei* has been recorded on various host plants, including Punnai (*Calophyllum inophyllum*), Noni (*Morinda citrifolia*) and guava (*Psidium guajava*) (30). The pest was later observed along the western Ghat coastal regions of Kerala and Karnataka in November 2018 (13). In Tamil Nadu, a survey of whitefly species affecting horticultural crops revealed the presence of *P. minei* on coconut (*Cocos nucifera*) and banana (*Musa* spp.) in Coimbatore (26). All four whitefly species (*Paraleyrodes minei*, *Aleurodicus rugioperculatus*, *Paraleyrodes bondari* and *Aleurotrachelus atratus*) coexist in coconut ecosystems in Tamil Nadu and contribute to crop damage. However, specific quantitative data on their individual or combined damage impact is currently unavailable. Their simultaneous presence poses a significant challenge for pest management, as they collectively affect plant vigor, promote sooty mold formation and reduce coconut yield.

Palm infesting whitefly, *Aleurotrachelus atratus*

Palm infesting whitefly was first described from coconut in Brazil in 1922, quickly spread to various regions, including Antigua, the Bahamas, Barbados, Bermuda, Colombia, Venezuela and Florida (USA) (31). *Aleurotrachelus atratus* has been reported to cause significant damage to coconut palms in the Comoro Islands (32) and has also been observed in the southwestern Indian Ocean islands (33). *Aleurotrachelus atratus* infests palm leaves, causing yellowing, wilting and premature leaf drop due to sap-sucking. The honeydew excreted by the whiteflies promotes sooty mold growth, which reduces photosynthesis and weakens the plant. Severe infestations lead to reduced yield in commercial palms and aesthetic damage in ornamental species. In England, large populations of *A. atratus* infesting African oil palm (*Elaeis guineensis*) were documented and it is believed that the species arrived in 2001 through coconut palms imported from the Netherlands (34).

In India, *A. atratus* was first reported in coconut plantations of Karnataka and on ornamental areca palm (*Dyopsis lutescens*) in the Mandya and Mysore districts (14). Subsequently, its presence was confirmed on coconut (*Cocos nucifera*) in the Dharmapuri and Krishnagiri districts of Tamil Nadu (35). Further reports from Kannur, Kerala, highlight its continued spread and potential impact on palm cultivation in the country (36).

Taxonomy and dynamics of invasive whiteflies in India

The whitefly fauna of India is characterized by a significant diversity, comprising a total of 66 genera. Of these, 64 belong to the subfamily Aleyrodinae (Westwood), which includes several economically important genera. Notable among these are *Bemisia* (38), *Trialeurodes* (39) and *Aleurothrix* (37). These genera are recognized for their roles as pests in agriculture, particularly due to their capacity to transmit plant viruses and cause substantial crop damage. In addition to Aleyrodinae, the subfamily Aleurodicinae (Quaintance & Baker) accommodates four genera: *Aleurodicus* (Douglas), *Aleuronudus* (Hempel), *Metaleurodicus* (Back) and *Palealeurodicus* (Martin). The diversity within these subfamilies underscores the ecological

complexity of whiteflies in India.

Among the notable invasive species in India are whiteflies from the genera *Aleurodicus*, including *A. dispersus* and *A. rugioperculatus*, along with two species from the genus *Paraleyrodes*: *P. minei* and *P. bondari*. The genus *Paraleyrodes* includes seventeen species, which contribute to the challenges of managing whitefly populations. This genus features species such as *P. citricolus*, *P. triangulae*, *P. goyabae*, *P. proximus*, *P. perseae*, *P. pseudonaranjae*, *P. singularis*, *P. urichii*, *P. citri*, *P. ancora*, *P. crateraformans*, *P. cervus*, *P. pulverans*, *P. perplexus* and *P. naranjae*, as documented previously (39, 27). The invasive whitefly complex has been taxonomically classified from kingdom to genus as follows: Animalia, Arthropoda, Insecta, Hemiptera, Sternorrhyncha, Aleyrodoidea, Aleyrodidae, Aleurodicinae and *Paraleyrodes*. This systematic classification highlights the hierarchical structure used in identifying and categorizing whiteflies, reflecting their biological relationships and evolutionary history.

Key characters of taxonomical identification

The puparium of *A. rugioperculatus* was identifiable by its broadly cordate vasiform opening, which is complemented by a spinulose operculum on the ventral-basal side and a distinctly rugose texture on the dorsal surface. It includes a pair of fine setae at the ventro-median position, while the lingula head extends beyond the vasiform opening, showcasing a finely spinulose texture with an acute tip. Four additional setae are located near the apex. This puparium can be clearly differentiated from *A. dispersus*, another species in India, by small compound pores on abdominal segments VII and VIII, a distinctly rugose operculum and an unusually narrowly acute lingual apex (40). The study highlighted distinct puparial characteristics that differentiate the rugose spiralling whitefly from the spiralling whitefly (27). The rugose spiralling whitefly exhibits a reticulated dorsal cuticle, compound pores on abdominal segments VII and VIII, surface corrugations on the operculum and an acutely shaped lingula. In contrast, the spiralling whitefly has a smooth cuticle, lacks compound pores on abdominal segments VII and VIII and possesses an oval-shaped lingula apex (6).

The puparial features of *P. bondari* consist of a larger cephalic pore and four abdominal compound pores, surrounded by an outer ring of ovoid cellular facets that resemble stylized flower petals. The last four abdominal compound pores are complemented by simple discoidal pores and 2-3 additional discoidal pores paired with two smaller abdominal pores, each about half the size. This arrangement results in 7-8 facets resembling flower petals. The male genitalia are notable for their distinctive aedeagus, which features a single dorsal and ventral horn at the apex and a pair of apicolateral processes.

The puparial features of *P. minei* include a larger cephalic pore, four abdominal compound pores and an outer ring of ovoid cellular facets that create a stylized flower petal appearance. The last four abdominal compound pores are accompanied by simple discoidal pores, 2-3 additional discoidal pores and two reduced abdominal pores, each about half the size of the larger ones. Together, these structures form 8-9 facets that mimic flower petals. The tongue-like lingula

extends beyond the posterior margin of the vasiform orifice and has two pairs of apical setae, while the operculum partially covers both the lingula and the vasiform orifice. The male claspers feature a robust nail and the aedeagus has a distinctive cockhead-shaped apex, which includes three short appendices on the upper and posterior surfaces, alongside two lengthy, thin appendices that project downward beneath the shorter anterior appendix. The distinguishing characters of Bondar's Nesting Whitefly and Nesting Whitefly were similarly outlined (40, 41). Both studies emphasize specific taxonomical traits that differentiate these species, providing valuable insights for accurate identification.

The puparium of *A. atratus* is elongated and oval-shaped, with a smooth dark cuticle. The marginal teeth are distinct and separated, featuring converging either subtruncate or rounded tips, each with serrated edges. Notably, no first abdominal or mesothoracic setae are present. The metathoracic setae extend beyond the second abdominal segment, while the eighth abdominal setae are longer than the vasiform orifice. The caudal setae are very long and located on tubercles. The submarginal area is characterized by rows of flat, elongated granules of similar size and the tip of the lingula is rounded.

Additionally, each puparium displays a distinct pair of diagnostic sub-marginal longitudinal cephalothoracic folds that extend into the abdomen. The same distinguishing characters were also noticed (40). Their descriptions provide key morphological traits for accurately identifying and differentiating *A. atratus* from other related species.

Species Validation by Morphological characterization

The life stages of the rugose spiraling whitefly (RSW) are marked by distinct characteristics. The adult female lays eggs in a spiral pattern on palm surfaces, while the nymphs exhibit subtle projections arranged in a tail-like formation. *A. rugioperculatus* nymphs undergo five instars, with the first instar being a crawler that hatches from the egg and seeks a feeding site using its needle-like mouthparts to extract plant sap. The puparium is convex, featuring a triangular rugose operculum and a pointed lingula. Adult RSW are robust, displaying a white coloration adorned with greyish-brown mottling on their wings (Fig. 1).

Adult rugose spiraling whiteflies have long, pincer-like appendages at the tip of their abdomen. The nymphs produce slender, waxy filaments and a dense cottony wax, with their coloration ranging from light to golden yellow (27, 42). RSW eggs are yellowish and elliptical, covered with a layer of white flocculent wax. During the immature stages, nymphs produce abundant wax filaments, including long, glassy, crystal-like rods and tufts of fluffy wax. Adult RSW are slightly larger than common whiteflies and are characterized by two light brown bars running along their wings (14, 23).

Paraleyrodes bondari, commonly known as Bondar's Nesting Whitefly, is characterized by its unique appearance and behavior. The adult whiteflies exhibit distinctive "X"-shaped oblique greyish stripes on their wings, which serve as a visual identifier for this species. These markings, combined with their small size, make them easily distinguishable from other whiteflies (Fig. 2).

One of the most notable features of *P. bondari* is its

nesting behavior. The females produce woolly wax nests that are typically located on the abaxial (underside) surface of palm leaves. These nests consist of a dense layer of waxy material, providing protection for the eggs and nymphs developing within (25).

One of the keys identifying features of *P. minei* is its wing structure, characterized by a median and forked radial vein, which distinguishes it from other whiteflies. Additionally, the presence of spine-like tarsal paronychium on the legs enhances its ability to adhere to host plants, an adaptation crucial for its survival. While *P. minei* shares similarities with *P. bondari*, it notably lacks the oblique grey stripes that are characteristic of the latter species. Furthermore, *P. minei* constructs loosely woven fuzzy wax nests, which serve as a protective environment for its eggs and nymphs. This nesting behavior is a significant aspect of its life cycle, reflecting its ecological adaptations. Egg-laying behavior is also noteworthy; *P. minei* produces cream-colored egg clusters with short stalks that transition to a pinkish hue during eclosion, indicating the developmental stages of the embryos within. The nymphs are described as flat and creamy-yellow, adorned with fiberglass threads on their dorsum, which provide an additional layer of protection against predators and environmental stressors.

In terms of sexual dimorphism, male *P. minei* individuals exhibit a smoky grey coloration, complemented by smoky grey wings. Their antennae are uniquely orange-tinged and whip-like, consisting of three segments, which play a role in sensory perception. In contrast, female whiteflies are predominantly white, featuring a grey blotch in the terminal area of their wings. Their antennae are four-segmented with a swollen second segment, further differentiating them from males (Fig. 3). The morphological traits of *Paraleyrodes minei* have been consistently documented, highlighting their importance in the identification and classification of this species within the Aleyrodidae family (43, 44).

The eggs and nymphs of *A. atratus* exhibit distinct behavioral and morphological traits, primarily congregating on the underside of coconut fronds. They are densely covered with flocculent white waxy material, which serves as a protective barrier over the black pupae beneath. In terms of size, adult *A. atratus* is larger than both *Paraleyrodes bondari* and *Paraleyrodes minei*, making them easily distinguishable in the field. A key feature of their wings is the absence of any wavy markings, which sets them apart from other species. These described features are essential for the identification and classification of *A. atratus*, aiding in the understanding of its ecological interactions and potential impact on coconut crops (14).

Biology and morphometric analysis

The detailed study of the biology and morphometric analysis of the invasive whitefly complex on coconut is summarized in Table 1. This table provides a comprehensive overview of key measurements, life cycle stages, and developmental durations for various species of whiteflies affecting coconut cultivation. It includes information on egg sizes, nymphal instar dimensions, pupal characteristics, and adult measurements, alongside the duration of each life cycle stage. The data highlights the differences and similarities among the invasive species.

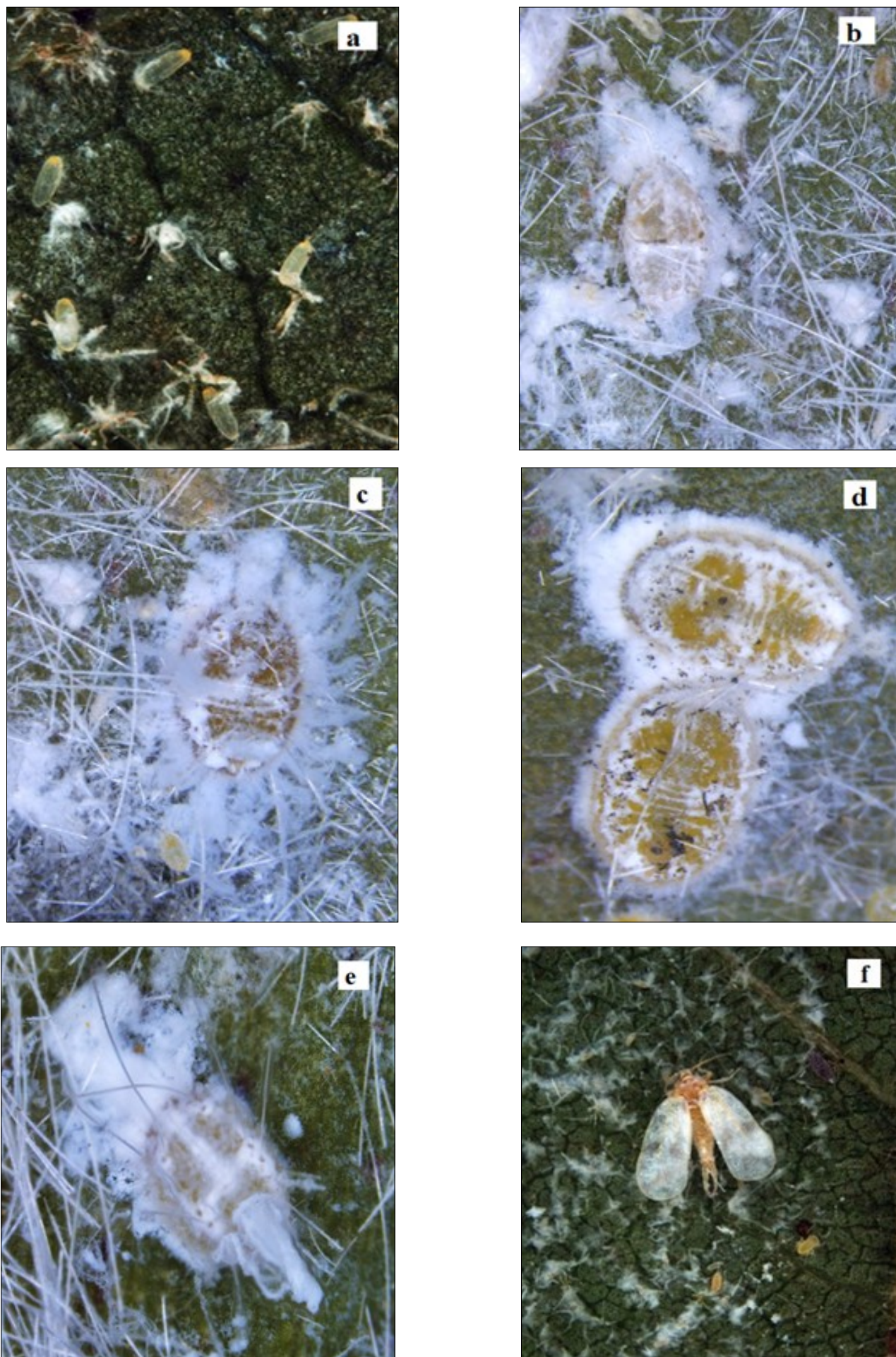


Fig. 1. a-h: Developmental stages of *A. rugioperculatus*: a, eggs are laid in a spiral pattern b, 1st nymphal instar c, 2nd nymphal instar d, 3rd nymphal instar e, 4th nymphal instar f: adult

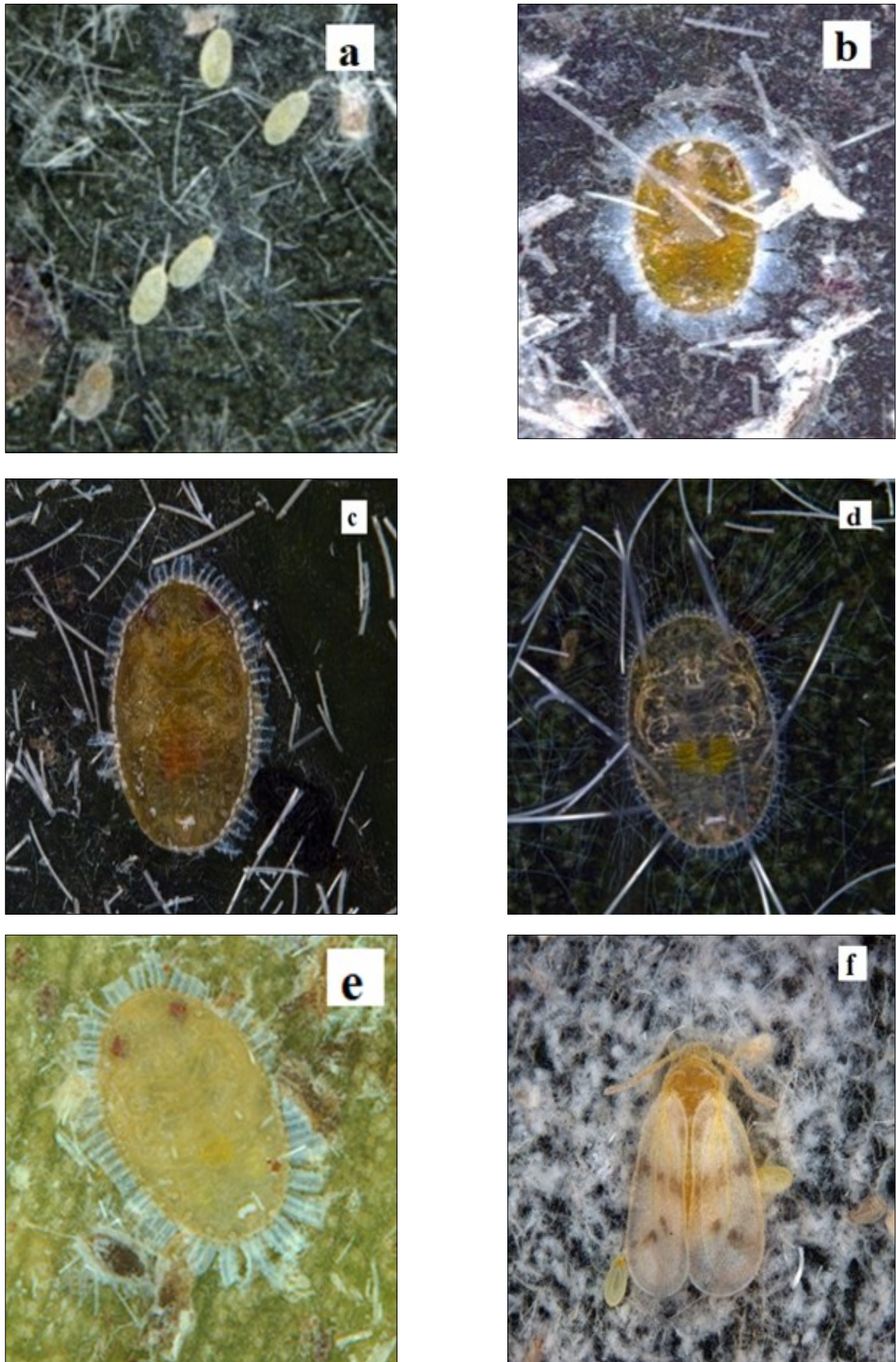


Fig. 2. a-e: *P. bondari* life stages: a, eggs; b-e, nymphs; f, male and female adult

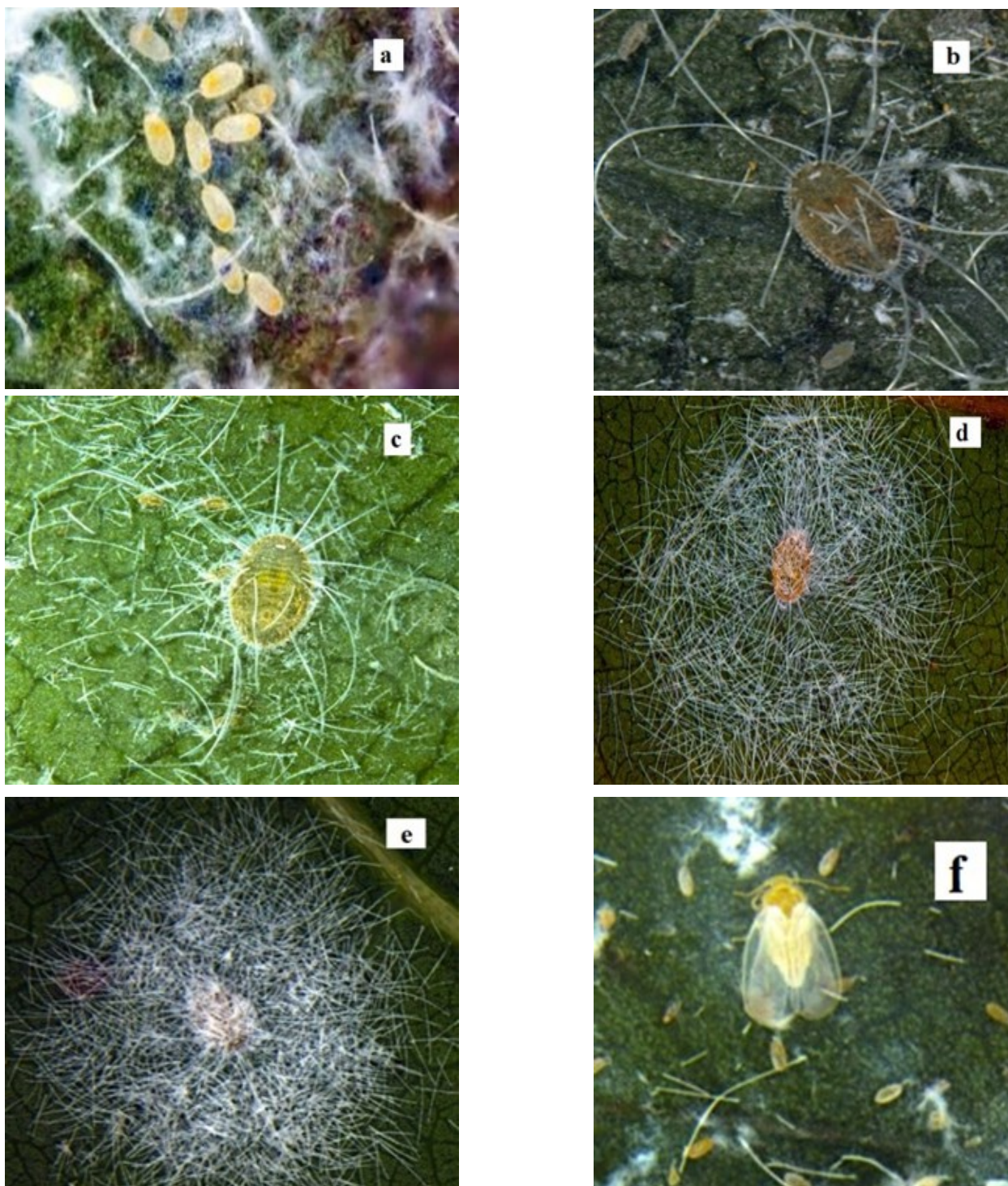


Fig.3: a-f: *P. minei* life stages: a, eggs; b-e, nymphs; f, adult

The life cycle of *A. rugioeperculatus* spans approximately 59 days, with the egg stage lasting about 6.9 days, nymphs about 19.57 days, and pupae around 10.9 days. Females lay eggs in a spiral pattern on leaf undersides, and the nymphal stage lasts about 27.7 days before transitioning to adulthood, which has an average lifespan of 20.5 days (11,45).

Morphometric measurements of rugose spiralling whiteflies revealed that male adults averaged 2.63 mm in length and 2.12 mm in width, while females measured 3.15 mm in length and 2.17 mm in width. The measurements across different life stages were as follows: eggs measured 0.34 mm in length, first instar nymphs 0.41 mm, second instar nymphs 0.73 mm, and the oval-shaped puparium 1.59 mm (46). Slightly different measurements were reported, with eggs averaging 0.24 mm in length. First instars measured 0.35 mm in length and 0.24 mm

in width, second instars 0.58 mm by 0.27 mm, third instars 0.83 mm by 0.38 mm, and fourth instars 1.08 mm by 0.70 mm. adult males averaged 2.27 mm in length and 1.30 mm in width, while females measured 2.59 mm in length and 1.71 mm in width (47).

Adults of *Paraleyrodes bondari* measure approximately 1.11 mm in body length (13). Morphometric measurements recorded eggs at 0.15 mm in length and 0.08 mm in width, nymphs at 0.46 mm by 0.36 mm, pupae at 0.59 mm by 0.41 mm, and adults at 1.09 mm in length and 0.73 mm in width (47). Eggs measured 0.21 mm by 0.10 mm, with first instar nymphs measuring 0.29 mm by 0.16 mm, second instars 0.52 mm by 0.35 mm, third instars 0.59 mm by 0.41 mm, and fourth instars 0.77 mm by 0.52 mm. Adults averaged 1.10 mm in length and 0.56 mm in width (48).

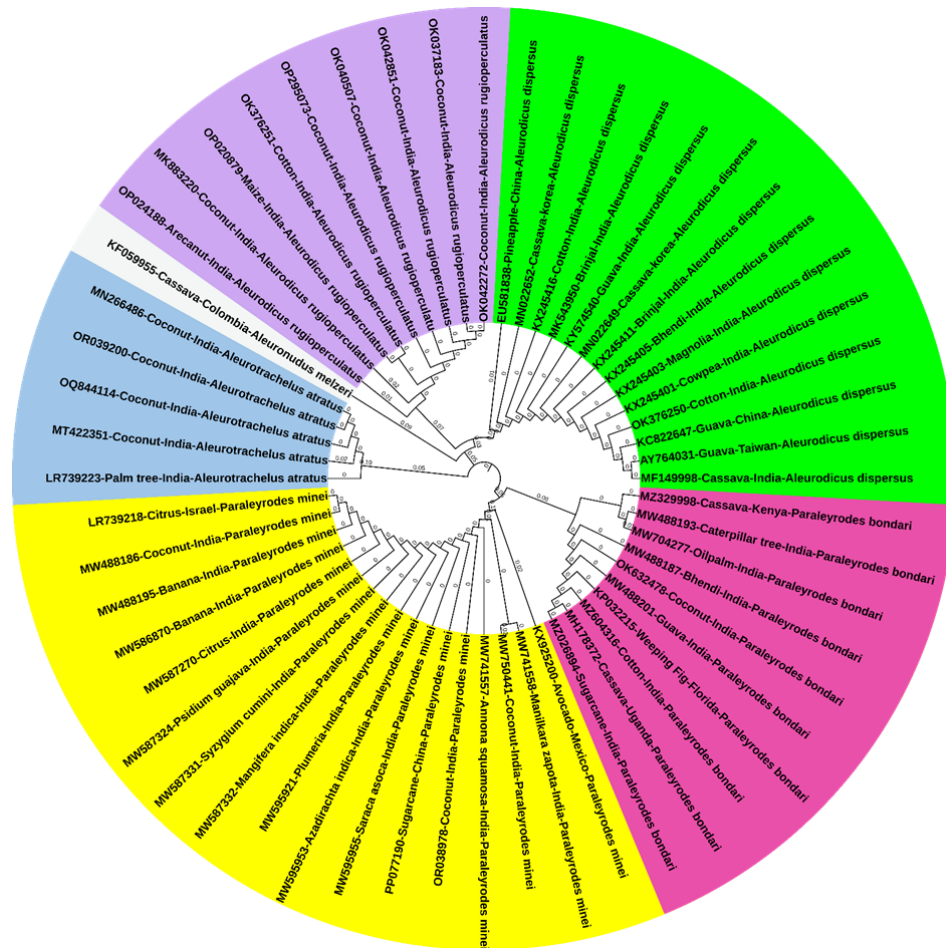


Fig. 4. Phylogeny tree analysis of invasive whiteflies in coconut

Table 1. Morphometric measurements and life stage durations of whitefly species reared on coconut

Life stages	Mean (± SE) (mm)		Mean (± SE) Duration (Days)
	Length	Breadth	
<i>Aleurodicus rugioperculatus</i>			
Eggs	0.26 ± 0.02	0.14 ± 0.02	6.54 ± 0.43
1st nymphal instar	0.37 ± 0.04	0.25 ± 0.02	5.51 ± 0.72
2nd nymphal instar	0.56 ± 0.04	0.27 ± 0.01	5.23 ± 0.48
3rd nymphal instar	0.87 ± 0.08	0.36 ± 0.01	8.12 ± 0.72
4th nymphal instar	1.11 ± 0.09	0.73 ± 0.08	10.1 ± 0.75
Adult	2.52 ± 0.08	1.71 ± 0.15	21.8 ± 2.54
Total life cycle	-	-	62.6 ± 0.64
<i>Paraleyrodes bondari</i>			
Eggs	0.18 ± 0.05	0.09 ± 0.02	5.24 ± 0.21
1st nymphal instar	0.26 ± 0.02	0.15 ± 0.01	3.18 ± 0.17
2nd nymphal instar	0.39 ± 0.04	0.28 ± 0.03	6.95 ± 0.23
3rd nymphal instar	0.48 ± 0.02	0.36 ± 0.02	6.72 ± 0.30
4th nymphal instar	0.63 ± 0.04	0.43 ± 0.07	4.37 ± 0.28
Adult	1.10 ± 0.01	0.72 ± 0.06	15.5 ± 0.37
Total life cycle	-	-	61.51 ± 0.92
<i>Paraleyrodes minei</i>			
Eggs	0.34 ± 0.02	0.22 ± 0.38	5.9 ± 0.20
1st nymphal instar	0.49 ± 0.02	0.54 ± 0.29	5.4 ± 0.34
2nd nymphal instar	0.57 ± 0.04	0.73 ± 0.59	3.5 ± 0.47
3rd nymphal instar	0.64 ± 0.07	0.87 ± 0.45	6.7 ± 0.28
4th nymphal instar	0.84 ± 0.03	0.93 ± 0.33	5.1 ± 0.44
Adult	1.11 ± 0.07	1.71 ± 0.15	11.2 ± 0.76
Total life cycle	-	-	44.6 ± 0.87
<i>Aleurotrachelus atratus</i>			
Eggs	0.12 ± 0.03	0.07 ± 0.01	5.4 ± 0.10
1st nymphal instar	0.29 ± 0.01	0.11 ± 0.07	11.7 ± 0.28
2nd nymphal instar	0.37 ± 0.03	0.21 ± 0.01	8.5 ± 0.04
3rd nymphal instar	0.52 ± 0.07	0.33 ± 0.03	7.3 ± 0.01
4th nymphal instar	1.03 ± 0.08	1.56 ± 0.19	5.9 ± 0.17
Adult	1.95 ± 0.05	1.20 ± 0.04	10.0 ± 0.01
Total life cycle	-	-	48.8 ± 0.61

* Mean length and width were calculated from 15 observations for each life stage. Mean duration was recorded from 15 samples for each life stage at the beginning

The life cycle of *P. bondari* lasts between 20 and 26 days on coconut, with four nymphal stages totaling 15.4 days. The first instar develops in about 3.2 days, the second and third instars take roughly 7 days, and the fourth instar lasts around 4.8 days. Adults have flattened wings that extend over the body, a pale-yellow color with a light wax coating, and a lifespan of approximately 16.7 days. Overall, the life cycle can extend to 35-40 days on cotton (49).

The nesting whitefly, *Paraleyrodes minei*, was a small insect whose morphological and developmental characteristics have been the focus of extensive research, shedding light on its life cycle and growth stages.

The eggs of *P. minei* are notably small, measuring approximately 0.368 ± 0.03 mm in length. After a period of incubation lasting around 6 to 7 days, these eggs hatch into first instar nymphs, also known as crawlers, which measure about 0.527 ± 0.04 mm. As the nymph's progress through their life cycle, they undergo several instars, each marked by significant changes in size. The second and third instar nymphs grow to about 0.739 ± 0.08 mm, while the fourth instar reaches a length of 0.867 ± 0.03 mm. Upon reaching adulthood, *P. minei* measures approximately 1.106 ± 0.09 mm in body length, positioning it as a relatively small member of the whitefly family (13).

The life cycle of *P. minei* consists of distinct stages, beginning with the egg stage, where eggs are laid on the undersides of leaves. Following the egg stage, the nymphs undergo four instars, each varying in duration: the first instar lasts about 3 days, the second around 5 to 7 days, the third approximately 4 to 5 days, and the fourth about 4 to 5 days as well. In total, the nymphal stages typically span between 15 to 20 days, influenced by environmental conditions and the health of the host plant. The entire life cycle of *P. minei*, from egg to adult, can take approximately 30 to 45 days under optimal conditions. While specific survival temperature ranges for *P. minei* are not extensively documented, studies on related whitefly species suggest that temperatures below 20°C or above 30°C can reduce survival rates.

Molecular characterization

Phylogenetic tree analysis

The analysis involved 56 nucleotide sequences of whitefly complexes specifically targeting the COI (Cytochrome c Oxidase I) gene region. These sequences were obtained from the NCBI database and represent whitefly populations from various countries: China, Korea, Kenya, Florida (USA), Uganda, Mexico, Israel, Taiwan, Colombia, and India.

The whitefly populations were classified into three major clades based on the analysis of their COI sequences. This study involved the annotation and manual curation of whitefly mtCOI sequences using the DNA MAN program before submission to GenBank. Sequence similarity was assessed through comparisons with GenBank reference sequences, and phylogenetic analysis included available mtCOI sequences, incorporating appropriate out-group species. Sequence refinement was conducted in BioEdit, with multiple sequence alignment performed using Clustal W in MEGA-X software. A phylogenetic dendrogram was constructed using the Neighbor-Joining method with 1000 bootstrap replicates in MEGA-X. The first clade comprises two species: *Paraleyrodes bondari* and

Paraleyrodes minei. The second clade was represented by *Aleurotrachelus atratus* from the same study. The third clade includes two species, *Aleurodicus rugioperculatus* and *Aleurodicus disperses*. The sequences were likely aligned and analyzed to determine genetic relationships and phylogenetic clustering based on the COI gene. The division into clades suggests distinct genetic groups within the whitefly populations studied. Various studies provide a comprehensive geographical representation of whitefly complexes, shedding light on their genetic diversity and evolutionary relationships. *Aleurodicus rugioperculatus* was amplified using a universal COX-I primer, resulting in a 658 bp sequence (7). Partial mitochondrial COX-I sequences of 675 bp and 621 bp were obtained from *Paraleyrodes bondari* (25,16). Genetic analysis revealed high nucleotide similarity among *P. bondari* populations across different regions (25). Kenyan sequences closely matched Indian isolates from guava (GenBank: MW488201) and coconut (GenBank: MW488198), with 99.84% and 100% similarity, respectively. A 632 bp sequence from Uganda (GenBank: MH178372) showed 100% similarity with a Florida isolate (GenBank: KP032215), indicating minimal genetic divergence. Likewise, Indian sequences (GenBank: MK333262) exhibited 100% similarity with those from Uganda and Florida, reinforcing genetic homogeneity across continents.

In India, *P. bondari* populations attacking the caterpillar tree (MW488193) and infesting oil palm (MW704277) are closely related. This suggests a genetic similarity between these two populations of *P. bondari* within India. In Uganda, the *P. bondari* population infesting cassava (MH178372) shows genetic similarity to the Indian population of *P. bondari* infesting sugarcane (MZ026894). This indicates a genetic relationship between these populations, despite the geographical distance between Uganda and India.

Manilkara zapota (MW741558) and coconut (MW750441) infesting populations of *P. minei* in India show a high similarity of 99%. This suggests that these two populations share a very recent common ancestry, despite infesting different host plants. Citrus (MW741558) infesting populations of *P. minei* in India are closely related to the Indian coconut (MW488186) infesting population. This indicates genetic similarity between *P. minei* populations infesting citrus and coconut in India. The remaining populations of *P. minei* were scattered into single clades, suggesting more genetic diversity compared to the highly similar populations.

All the populations of *A. atratus* from coconut and palm trees in India formed a single cluster. This clustering suggests that these populations are genetically very similar to each other. Populations of *A. rugioperculatus* infesting coconut (sequences OK037183 and OK042272) in India were found to be 99.9% similar to each other based on the comparison of the data available in NCBI. This high similarity indicates that these populations are very closely related genetically, likely suggesting a recent common ancestry or ongoing gene flow between them. Indian sequences of *A. rugioperculatus* infesting maize (OP020879) were found to be closely related to sequences from cotton (OK376251) infesting populations. This suggests a genetic affinity between the populations infesting different host plants (maize and cotton) in India.

The population of *A. dispersus* from Taiwan infesting maize (AY764031) was found to be genetically close to the population infesting cassava (MF149998) in India. This genetic closeness suggests that despite the geographical and host plant differences, these populations of *A. dispersus* share a significant genetic similarity. In summary, the study analyzed 56 COI sequences of whitefly complexes from diverse geographic locations, identifying three major clades corresponding to different species or groups within the whitefly populations. This approach helps in understanding the genetic diversity and relationships among whitefly populations on a global scale. (Fig. 4).

Molecular identification of *A. rugioperculatus* utilized the cytochrome oxidase I gene (658 bp), registered as GenBank Acc. No. KY209909 (7). The same gene was sequenced for multiple accession numbers (MK883218, MK883219, MK883220, MK926750, MK926751) (50). *A. rugioperculatus* was documented in West Bengal and recorded under Accession No. OP024192 (51). For *P. bondari*, a 632 nt mtCOI sequence matched 100% with samples from Uganda (GenBank Acc. No. KP032215) (23). Its presence was confirmed with sequence ON739183 (52), while additional molecular analysis was conducted under Accession No. OP024193 (51). *P. minei* was characterized through DNA extraction and COI gene amplification (13). *A. atratus* was listed under GenBank Accession No. MT422351 (53), with further identification corresponding to OQ844114 (54).

Trends in Research on Invasive Whiteflies: A Bibliometric Analysis

Search engine and data

The bibliometric mapping approach is data-driven, relying extensively on computer algorithms and visualization techniques. It visually represents a topic by illustrating the relationships between key terms in the field. One of the most widely used software tools for this purpose is VOS viewer (developed by the Centre for Science and Technology Studies, 2018), which generates co-occurrence maps using keywords (both author-provided and indexed). The maps typically guide the analysis, but expertise in the field remains essential for accurately interpreting them. Bibliometric mapping also produces clusters of keywords (Whitefly or *Alerurodicus* or *Paraleyrodes* or *Aleurotrachelus* and Invasive or Invasion) which require expert review. The expert must analyse each cluster and make sense of the data. This approach has the advantage of reducing bias, as the expert is not limited by their own area of specialization (55). However, a drawback of this type of study is that some valuable publications may be overlooked due to the vast number of documents analysed. Finally, it is worth noting that bibliometric studies do not involve human or animal subjects, and thus ethical approval from an Institutional Review Board is not required. This literature review employed a quantitative approach, utilizing two methods: performance analysis (examining publications based on authors, countries, and institutions) and science mapping (using bibliometric software) (56). The analysis of publications was carried out through keyword-based studies.

A bibliometric analysis was conducted using the Dimensions AI database, focusing on 446 research articles related to invasive whiteflies and four key species: *Aleurodicus*

rugioperculatus, *Paraleyrodes bondari*, *Paraleyrodes minei*, and *Aleurotrachelus atratus*. Initially, searches using these species' names as keywords within titles, abstracts, keywords, and full-text papers yielded 446 documents, which were analysed for country-wise contributions. For analyses of annual scientific production, average citations per year, most relevant sources, most relevant authors, globally cited documents and country-wise scientific production, the species names were used as keywords to search within titles, abstracts, and keywords, resulting in 169 documents. The Bibliometrix R package facilitated a comprehensive exploration of research trends, authorship patterns, and thematic developments, while VOSviewer (version 1.6.20) was employed to enhance and refine the analysis further. These four species of whiteflies were recently introduced in India, and there are limited research papers available on the topic. As a result, we used a minimal number of sources for the bibliometric analysis.

Results

Bibliometric coupling of countries, as shown in (Fig. 5), revealed India and the United States as the central hubs of research, with strong collaborative links to countries such as the United Kingdom, China, and Brazil. The network visualization also highlights the emergence of recent contributions from countries like Indonesia and Bangladesh, underscoring a growing interest in these mite species in diverse regions. These findings provide insights into the geographical distribution and intensity of research efforts on these species. (Fig. 6), presents author-wise information on whitefly research from 1994 to 2024. The data reveals that Selvaraj has authored the highest number of documents, followed by Sundararaj, Hedge and Vinayaka. The coloured connecting lines represent collaborations between these authors.

(Table 2) and (Fig. 7), present data on annual scientific production, indicating that whitefly research began in 1996. The peak in publications occurred in 2023 with 31 articles, followed by 30 articles in 2022 and 23 articles in 2021. (Table 3 and Fig. 8), provide data on average citations per year, showing that 2023 recorded the highest number of citations with 31, surpassing all other years. (Table 4) and (Fig. 9), highlight the most relevant sources of whitefly research across the top 15 countries. The findings reveal that the Indian Journal of Entomology & Phyt parasitica published the highest number of articles (12), followed by Research Square (9 articles), International Journal of Tropical Insect Science (7 articles), and Journal of Biological Control (7 articles). (Table 5 and Fig. 10), present the top 10 most relevant authors who have contributed to research on invasive whiteflies. The data shows that Selvaraj K published the highest number of articles (15), followed by Joseph Rajkumar A (11 articles) and Hedge (8 articles). (Table 6) and (Fig. 11) highlight the top 10 most cited papers and authors in the field of invasive whiteflies, including globally cited documents. The results show that Sundararaj R (2017) received the highest number of citations (54), followed by Francis AW (2016) with 38 citations. (Table 7 and Fig. 12), present country-wise scientific production, with the results showing that India leads in research output, followed by the USA and the UK.

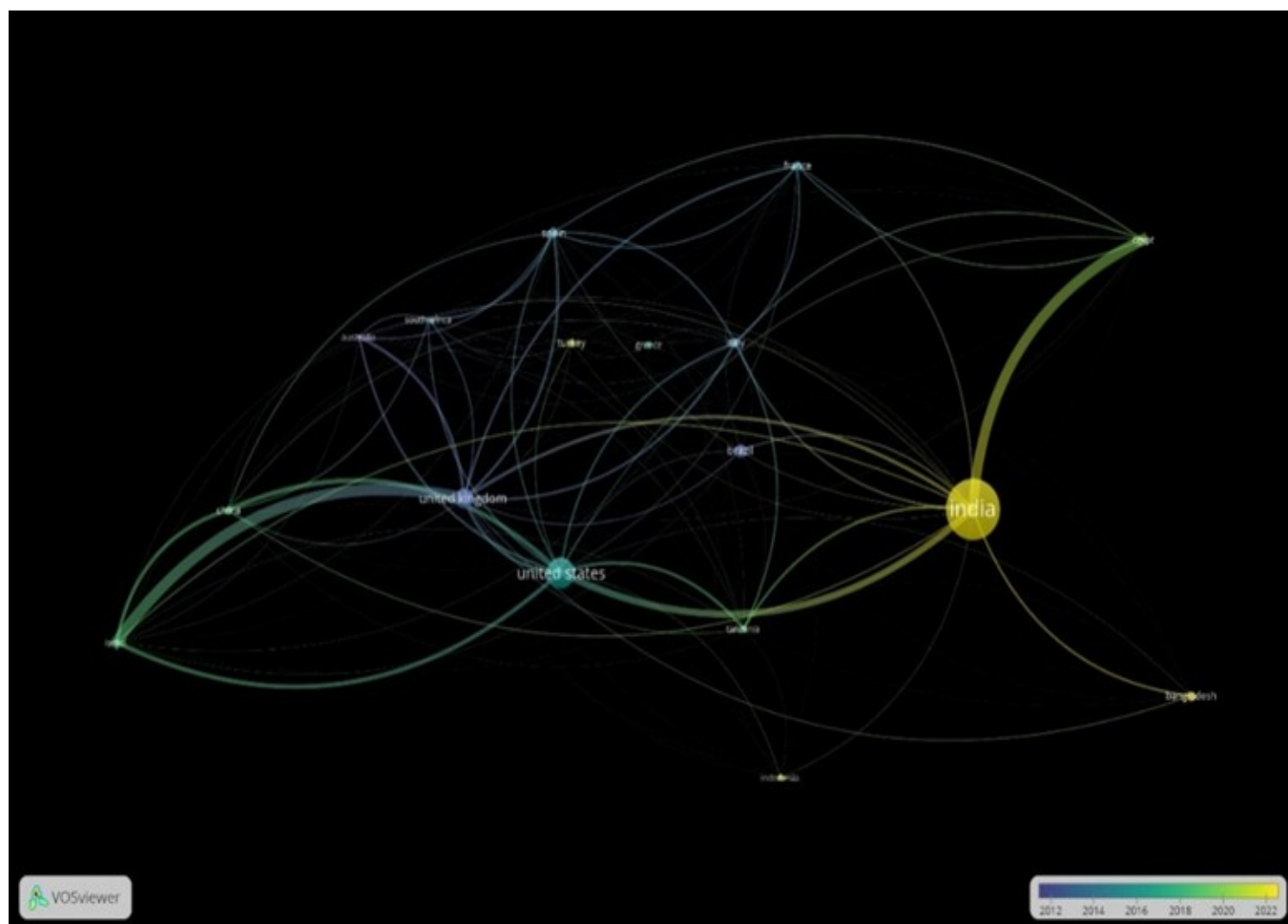


Fig. 5. VOS viewer overlay visualization for invasive whiteflies country wise from 2012 to 2024

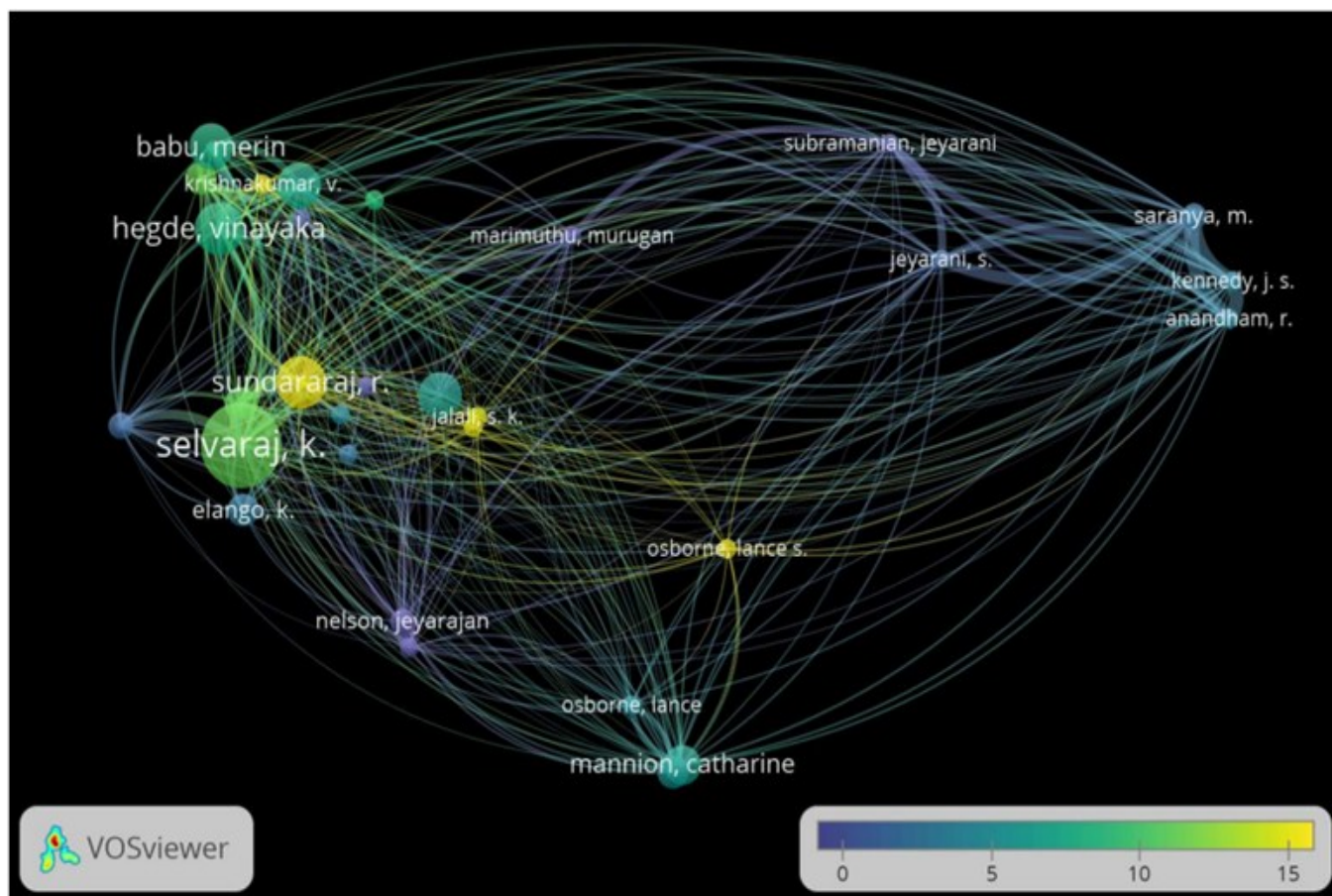


Fig. 6. VOS viewer overlay visualization for author wise whitefly documents information from 1994 to 2024

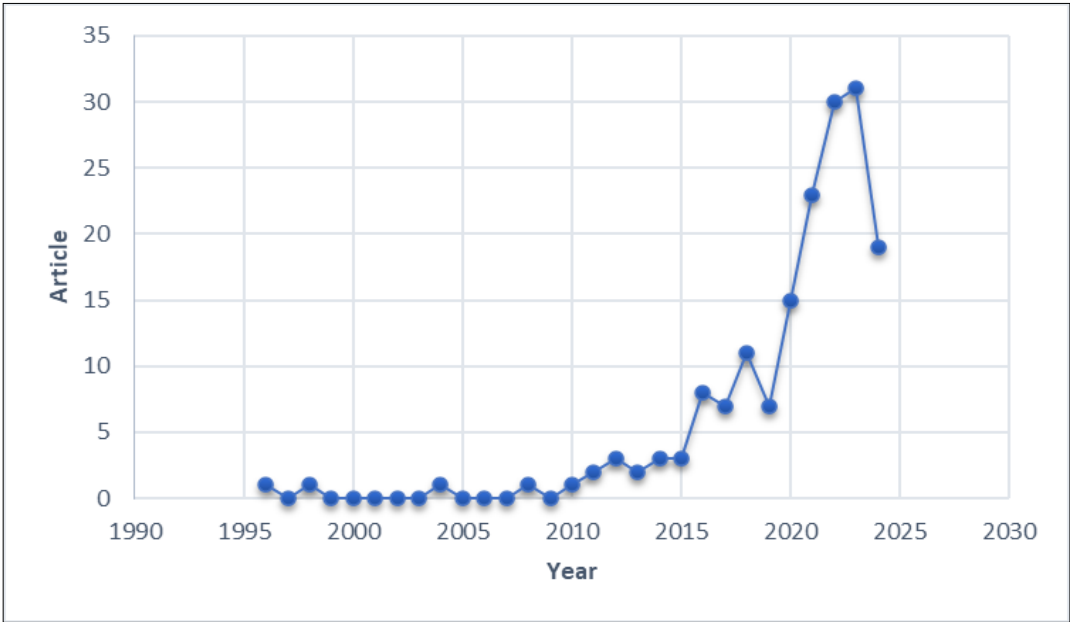


Fig. 7. Annual scientific productionof invasive whiteflies

Table 2. Annual scientific productionof invasive whiteflies

Year	Articles
1996	1
1997	0
1998	1
1999	0
2000	0
2001	0
2002	0
2003	0
2004	1
2005	0
2006	0
2007	0
2008	1
2009	0
2010	1
2011	2
2012	3
2013	2
2014	3
2015	3
2016	8
2017	7
2018	11
2019	7
2020	15
2021	23
2022	30
2023	31
2024	19

Table 3. Average citations per yearof invasive whiteflies

Year	Mean TC per Art	N	Mean TC per Year	Citable Years
1996	21	1	0.72	29
1998	9	1	0.33	27
2004	3	1	0.14	21
2008	2	1	0.12	17
2010	31	1	2.07	15
2011	5.5	2	0.39	14
2012	9	3	0.69	13
2013	12.5	2	1.04	12
2014	2	3	0.18	11
2015	7	3	0.7	10
2016	10.38	8	1.15	9
2017	13.14	7	1.64	8
2018	4.18	11	0.6	7
2019	9.14	7	1.52	6
2020	3.33	15	0.67	5
2021	4.04	23	1.01	4
2022	2.1	30	0.7	3
2023	0.65	31	0.32	2
2024	0.11	19	0.11	1

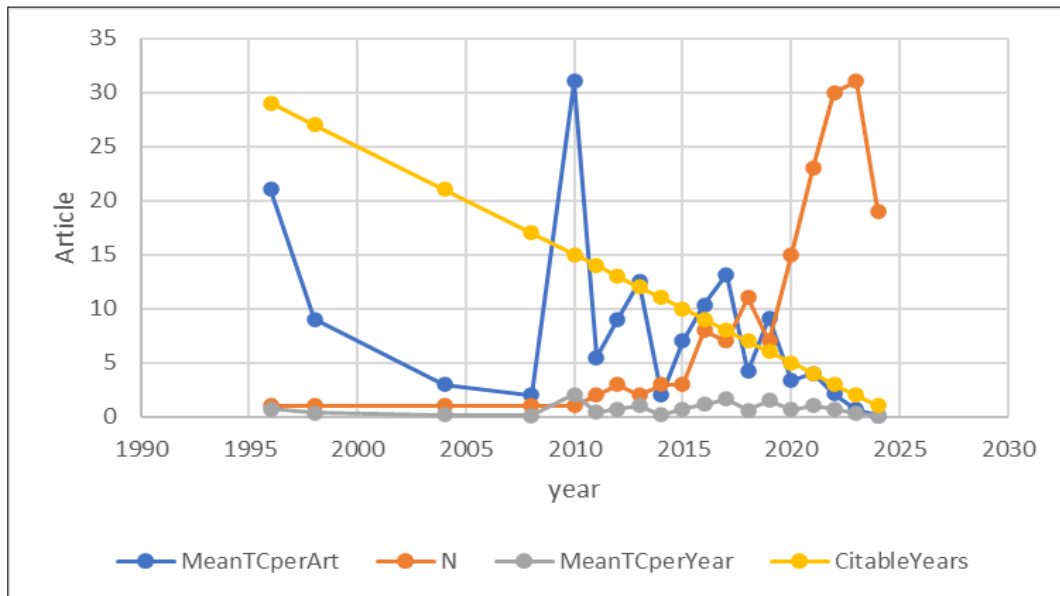


Fig. 8. Average citations per year of invasive whiteflies

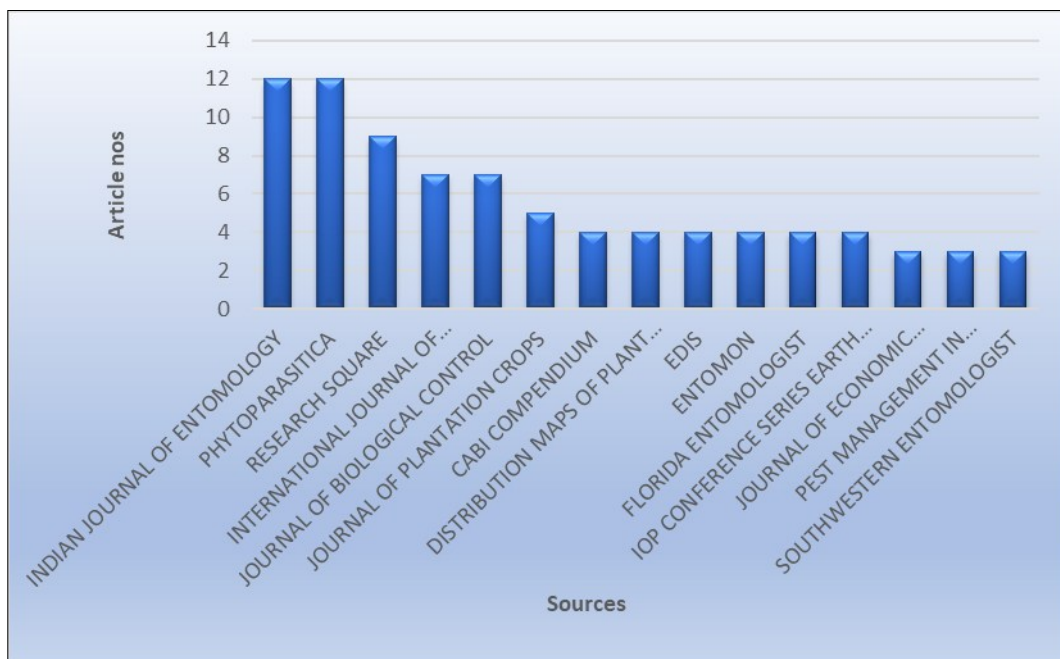


Fig. 9. Most relevant sources of invasive whiteflies.

Table 4. Most relevant sources of invasive whiteflies

Sources (Journal name)	Articles
Indian Journal of Entomology	12
Phytoparasitica	12
Research Square	9
International Journal of Tropical Insect Science	7
Journal of Biological Control	7
Journal of Plantation Crops	5
CABI Compendium	4
Distribution Maps of Plant Pests	4
EDIS	4
Entomon	4
Florida Entomologist	4
IOP Conference Series Earth and Environmental Science	4
Journal of Economic Entomology	3
Pest Management in Horticultural Ecosystems	3
Southwestern Entomologist	3

Table 5. Most relevant authors of invasive whiteflies

Authors	Articles	Articles Fractionalized
Selvaraj K	15	3.77
Josephraj Kumar A	11	1.77
Hedge V	8	1.38
Babu M	7	1.13
Sundararaj R	7	1.97
Elango K	6	2.25
Gupta A	6	2.04
Mannion C	6	1.75
Sumalatha BV	6	1.58
Mohan C	5	0.72

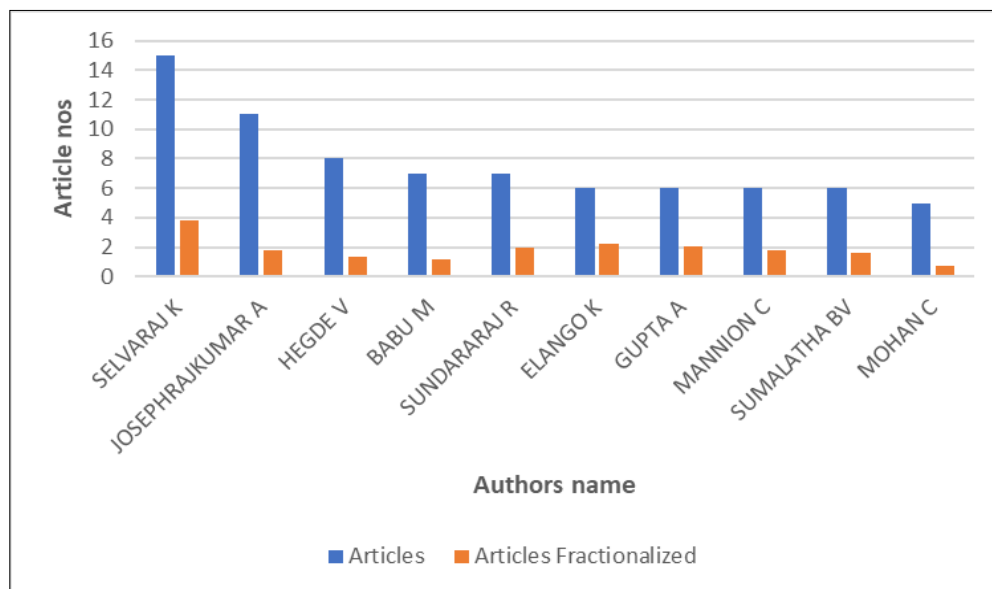


Fig. 10. Most relevant authors of invasive whiteflies

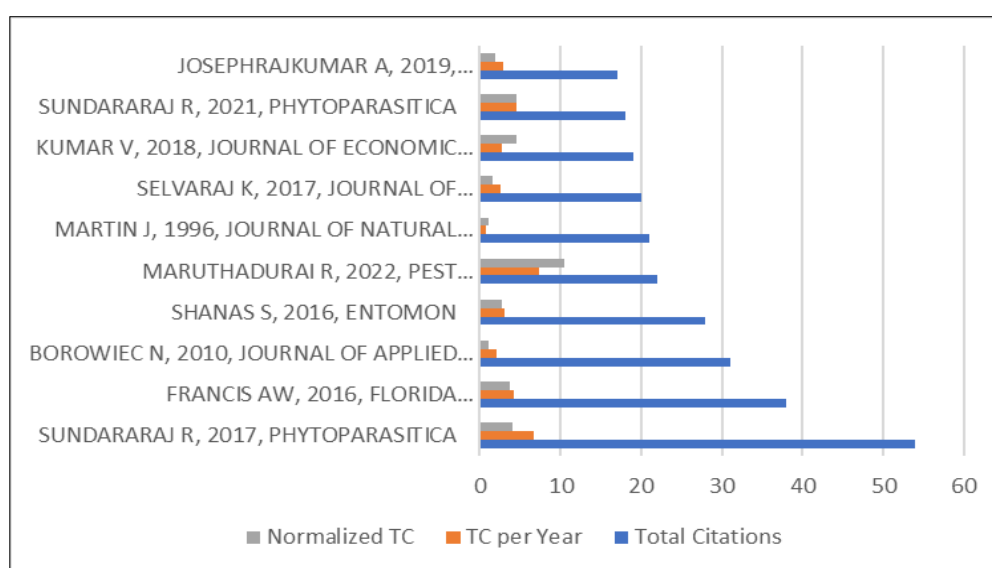


Fig. 11. Globally cited documents of invasive whiteflies

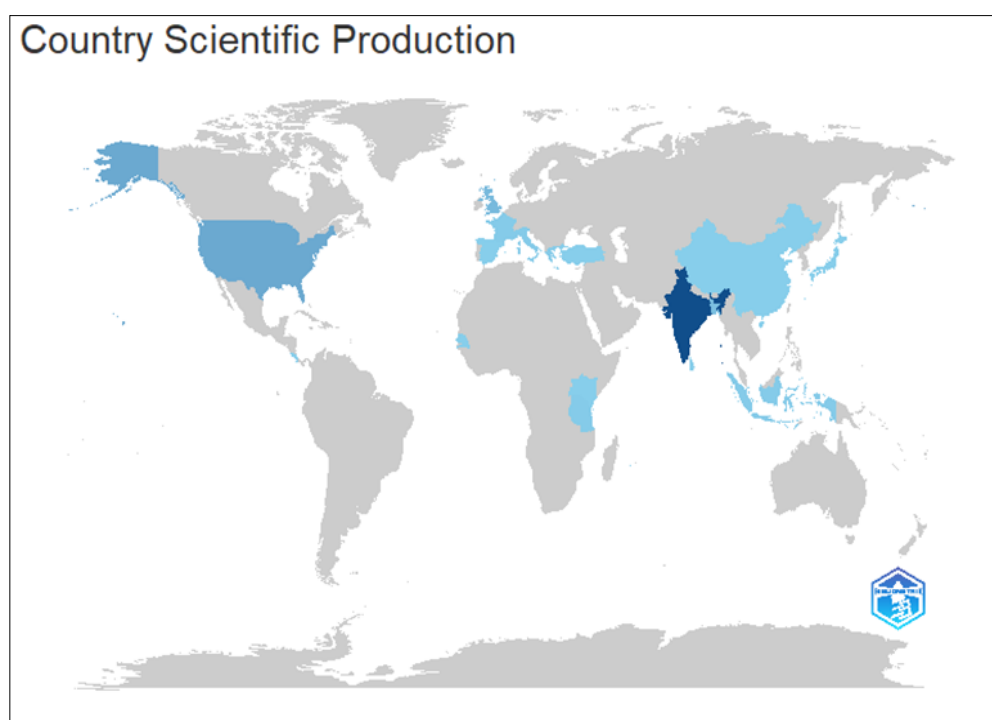


Fig. 12. Country-wise scientific production of invasive whiteflies

Table 6. Globally cited documents of invasive whiteflies

Paper	DOI	Total Citations	TC per Year	Normalized TC
Sundararaj R, 2017, Phytoparasitica	10.1007/S12600-017-0567-0	54	6.75	4.11
Francis AW, 2016, Florida Entomologist	10.1653/024.099.0134	38	4.22	3.66
Boroweic N, 2010, Journal of Applied Entomology	10.1111/J.1439-0418.2009.01450.X	31	2.07	1.00
Shanas S, 2016, Entomon	10.33307/ENTOMON.V4I14.227	28	3.11	2.70
Maruthadurai R, 2022, Pest Management Science	10.1002/PS.7199	22	7.33	10.48
Martin J, 1996, Journal of Natural History	10.1080/00222939600771081	21	0.72	1.00
Selvaraj K, 2017, Journal of Biological Control	10.18311/JBC/2017/16015	20	2.50	1.52
Kumar V, 2018, Journal of Economic Entomology	10.1093/JEE/TOY056	19	2.71	4.54
Sundararaj R, 2021, Phytoparasitica	10.1007/S12600-021-00919-7	18	4.50	4.45
Josephraj Kumar A, 2019, Phytoparasitica	10.1007/S12600-019-00741-2	17	2.83	1.86

Table 7. Country-wise scientific production of invasive whiteflies

Region	Freq
India	49
USA	14
UK	8
Bangladesh	6
France	2
Greece	2
Indonesia	2
Italy	2
Tanzania	2
China	1
Costa Rica	1
Japan	1
Kenya	1
EU	1
Senegal	1
Spain	1
Sri Lanka	1
Turkey	1
Uganda	1

Symptoms of damage and yield loss by invasive whiteflies

The nymphs of whiteflies feed on the sap from the underside of leaves, causing honeydew to exude onto the upper surfaces of leaves. This honeydew promotes the growth of the *Capnodium* fungus, resulting in a black, sooty appearance on affected plants and also negatively impacts photosynthesis, leading to physiological disorders, leaf deformities, immature nut drop, and stunted growth, ultimately reducing nut production.

Surveys conducted in Tamil Nadu, Kerala, Andhra Pradesh, and Karnataka showed significant variation in infestation severity, with coconut palms experiencing 40-60% damage and banana leaves sustaining 25-40% damage (7). Infested trees were easily identifiable due to the thick sooty mold covering, which caused frond drooping and wilting symptoms (10, 21). *A. rugioperculatus* has caused significant damage to coconut crops, particularly in coastal regions like Mangalore and Udupi, where infestations led to losses of 20-35% (7). A study in Jashore during 2019 found infestation rates between 46.66% and 68.33%, with Magura Sadar Upazila experiencing the highest levels (68.33%) (57). State assessments indicated infestation levels ranging from 20% to 100%, with native coconut varieties showing higher susceptibility (85.7%) compared to dwarf varieties (81.2%) (58). Seasonal trends revealed peaks in April-May and September-October, influenced by temperature fluctuations (59). Varying

yield losses were reported in hybrid palms, emphasizing the economic impact of these infestations (60).

In Tamil Nadu, Coimbatore district had the highest infestation (62.86%) from August 2017 to February 2019, with subsequent surveys revealing even higher rates in 2019-20, particularly in Tirunelveli (75.4%) and Kanyakumari (75.8%) (10,44). Surveys in Ratnagiri, Maharashtra, noted peak infestations during the rainy season (61).

Nests of *P. minei* are small and waxy white, formed from the secretions of females and filamentous wax rods from late instar nymphs (29). These whiteflies establish 3 to 30 nests on coconut leaflets, promoting intense sooty mold growth that adversely affects plant health (25). The damage caused by *A. atratus* is intensified by the sooty mold developing on honeydew excreted by the whiteflies, significantly impacting coconut palm growth and yield (32). Research in Inhambane province revealed that *A. atratus* was the most prevalent whitefly species, constituting 75% of infestations, while *Bemisia tabaci* was the least common (4.3%). Notably, a 1% increase in whitefly severity was associated with a yield loss of approximately 77.13 kg/ha (62). Additionally, *A. atratus* was linked to a staggering 55% economic yield loss for coconut growers (14).

Host plants

Coconut trees face year-round pest threats, intensified by climate change, insecticide resistance, and habitat destruction. The decline of natural enemies due to pesticide overuse and the spread of invasive pests through trade further worsen infestations. Sustainable integrated pest management (IPM) is crucial for effective control and long-term coconut production. Key pests include the Rugose Spiraling Whitefly (*Aleurodicus rugioperculatus*), Bondar's Nesting Whitefly (*Paraleyrodes bondari*), the Nesting Whitefly (*Paraleyrodes minei*) and the Palm Infesting Whitefly (*Aleurotrachelus atratus*), all of which have caused significant damage in major coconut-growing regions of India since their introductions in 2016, 2018, and 2019. In this study, the author documented several host plants affected by *P. bondari* for the first time. These host plants include red ginger, snake plant, jasmine, and egg fruit. This finding enhances our understanding of the ecological impact of *P. bondari* and highlights its potential threat not only to coconut plantations but also to other ornamental and agricultural crops. These invasive whiteflies are polyphagous, allowing them to feed on a wide range of host plants. While they primarily target coconut trees and other broad-leaved

plants in their native habitats, their host range has expanded to include various economic and horticultural crops, as well as weed species. For detailed information on host plants affected by these invasive whiteflies, refer to (Supp Table 1).

Population dynamics

In Coimbatore, Tamil Nadu, it was found that dwarf and hybrid coconut palms aged 4-6 years were highly susceptible to RSW, with the lower leaves exhibiting higher infestation rates ranging from 18 to 37 nymphs/cm² (63). Nymph populations were reported to range from 26.02 to 27.72 per leaflet, while puparium populations varied between 33.12 and 33.64 (55). In Chhattisgarh, RSW densities ranged from 14.2 to 30.6 per cm², with the highest density observed in Gautami Ganga (64). An average of 21.05 spirals per leaflet was found in East Godavari, while West Godavari recorded a significantly higher average of 124.09, indicating substantial damage across leaflets, petioles, and nuts (65). Minimal infestations were noted during the rainy season, with a significant increase in summer, peaking at 161 nymphs per leaf in October (46).

Infestation levels in Karnataka varied, with lower numbers recorded in the northern transition zone and significantly higher levels in the southern zone (66). Peak whitefly populations reached 34.1 in April (59), with fluctuations ranging from 4.24 to 102.87 adults per frond, peaking in mid-April (65). In Veppankulam, 28.6 adults per leaflet were documented (67), while egg spirals and nymph counts ranged from 9.36 to 23.41 and 13.41 to 34.17, respectively (68). Surveys in Tamil Nadu revealed adult populations between 29.50 and 34.60 per leaflet, with the highest counts observed in Kanyakumari (47). In coastal districts of Bangladesh, the highest RSW abundance was recorded in Khulna, with 23 egg spirals and 34 nymphs per leaflet, whereas Patuakhali showed lower counts (68).

Population Dynamics Research has highlighted the population trends of *P. bondari* in various regions. *P. bondari* was reported to have a nymphal population of approximately 8.04 nymphs per 30 cm leaflet in coconut, indicating a concerning level of infestation (16). More recently, a significant increase in population was observed, with 31.1 adults per leaflet recorded in Dharmapuri (67). Biweekly surveys conducted in southern Tamil Nadu from December 2020 to August 2021 revealed notable variations in whitefly populations. Kanyakumari recorded the highest nymph population at 35.31 per leaflet and the highest adult population at 34.84 per leaflet. In contrast, Tenkasi had the lowest nymph count at 22.79, while Thoothukudi reported the lowest adult count at 24.19 (47).

Natural enemies

Controlling invasive whiteflies through the use of natural enemies, such as predatory insects and parasitoids, offers a sustainable and environmentally friendly method for managing their populations. Details on natural enemies of invasive whiteflies can be found in (Table 8). Whiteflies are known for their rapid reproduction and damaging effects on crops, but their numbers can be effectively reduced by leveraging natural predators. Beneficial insects like ladybugs and lacewings actively seek out and consume whiteflies at various life stages, significantly diminishing their populations and mitigating plant damage. Additionally, parasitoids, such as certain wasp species, enhance biological control by laying their

eggs inside whitefly's nymphs. As the parasitoid larvae develop, they feed on the host, leading to its death and preventing further reproduction. This disrupts the whitefly life cycle while minimizing the reliance on chemical pesticides, which can harm non-target organisms and the environment.

Management

Invasive whiteflies pose a significant threat to coconut palms by sucking sap and depositing honeydew, which encourages the growth of sooty mold. Effective management of these pests requires an integrated approach, combining cultural, biological, chemical, and physical control methods. Cultural practices that interrupt the whitefly life cycle and reduce favourable conditions are essential. Crop rotation with non-host plants can help break the pest's life cycle and limit population growth (69). Regular pruning of infested fronds and removal of dead leaves can also effectively lower whitefly populations (70). Additionally, high-pressure water sprays can dislodge whiteflies from coconut leaves, especially during the early stages of infestation (61). Removing weeds that act as alternative hosts for whiteflies can significantly reduce the risk of infestation. Research in various cropping systems has identified several weed species that support whitefly populations, including *Abutilon indicum* (Indian mallow), *Chrozophora rottleri* (suryavarti), *Solanum nigrum* (black nightshade), and *Hibiscus ficulneus* (white wild musk mallow) (ISWS). Removing these weeds disrupts the whitefly life cycle and reduces infestation risks. On the other hand, certain non-host plants can help deter whiteflies by acting as repellents or trap crops. Examples include marigold (*Tagetes spp.*), neem (*Azadirachta indica*), lemongrass (*Cymbopogon spp.*), and basil (*Ocimum basilicum*), which have been observed to repel whiteflies or reduce their populations in agricultural settings (71). Trap cropping with plants like marigolds or sunflowers, which attract whiteflies, can divert them away from the main crops (72). Additionally, intercropping with non-host plants can make the environment less conducive to whitefly infestations, reducing their spread (73). Physical and mechanical methods are also effective, especially in the early stages of infestation. For instance, placing yellow sticky traps around coconut plantations helps monitor and capture adult whiteflies, as they are drawn to the yellow color and become trapped (74). Washing infested leaves with a strong jet of water is another practical method to knock down whiteflies, particularly when used in combination with other control strategies (61). Fungal pathogens like *Beauveria bassiana* and *Isaria fumosorosea* are effective in controlling whiteflies by infecting and killing them (75). While the development of whitefly-resistant coconut varieties is ongoing, breeding programs aim to provide a long-term solution for managing these pests (76). Horticultural oils and neem-based products are effective against whitefly nymphs, with neem oil offering both repellent and insecticidal properties (61). Insect Growth Regulators (IGRs), like buprofezin, target immature whitefly stages, reducing future populations while sparing beneficial organisms (77). Systemic insecticides, such as imidacloprid and thiamethoxam, can control whiteflies, but should be used sparingly to prevent resistance (78). Sooty mold, a secondary issue caused by honeydew secretions, can be managed by controlling whiteflies and cleaning affected leaves with water or a mild soap solution to restore photosynthesis (69).

Table 8. Natural enemies of invasive whiteflies

S. No.	Predators	Family & Order	References
Predators of invasive whiteflies			
1) Rugose spiralling whitefly, <i>Aleurodicus rugioperculatus</i>			
	<i>Nephaspis oculata</i> Blatchley.	Coccinellidae: Coleoptera	
	<i>Azya orbiger a orbiger a</i> Mulsant	Coccinellidae: Coleoptera	
	<i>Chilocorus cacti</i> L.	Coccinellidae: Coleoptera	
	<i>Cryptolaemus montrouzieri</i> Mulsant.	Coccinellidae: Coleoptera	
	<i>Delphastus pallidus</i> LeConte.	Coccinellidae: Coleoptera	
	<i>Harmonia axyridis</i> Pallas.	Coccinellidae: Coleoptera	
	<i>Hyperaspis bigeminata</i> Randall.	Coccinellidae: Coleoptera	
	<i>Cybocephalus</i> spp. Erichson.	Cybocephalidae: Coleoptera	(95)
	<i>Chrysopid</i>	Chrysopidae: Neuroptera	
	<i>Ceraeochrysa</i> spp. Adams.	Chrysopidae: Neuroptera	
	<i>Psyllobora parvnotata</i> Casey.	Coccinellidae: Coleoptera	
	<i>Mallada</i> spp. Navas.	Chrysopidae: Neuroptera	(61)
	<i>Dichochrysa astur</i> Banks	Chrysopidae: Neuroptera	(7)
	<i>Stethorus</i> spp. Weise.	Coccinellidae: Coleoptera	
	<i>Menochilus sexmaculatus</i> F.	Coccinellidae: Coleoptera	
	<i>Chilocorus nigrita</i> Fabricius.	Coccinellidae: Coleoptera	
	<i>Scymnus nubilus</i> Mulsant.	Coccinellidae: Coleoptera	
	<i>Chrysoperla zastrowi sillemi</i> Esben – Petersen.	Chrysopidae: Neuroptera	
	<i>Coccinella transversalis</i> F.	Coccinellidae: Coleoptera	
	<i>Mallada desjardinsi</i> Navas.	Chrysopidae: Neuroptera	(8)
	<i>Propylea dissecta</i> Mulsant.	Coccinellidae: Coleoptera	
	<i>Scymnus saciformis</i> Motschulsky.	Coccinellidae: Coleoptera	
	<i>Pseudomallada astur</i> Banks.	Chrysopidae: Neuroptera	(14)
	<i>Cybocephalus indicus</i> Tian & Ramani.	Nitidulidae: Coleoptera	
	<i>Mallada astur</i> Banks.	Chrysopidae: Neuroptera	
	<i>Mallada boninensis</i> Okamoto.	Chrysopidae: Neuroptera	
	<i>Cheilomenes sexmaculata</i> Fab.	Coccinellidae: Coleoptera	(15)
	<i>Curinus coeruleus</i> Mulsant.	Coccinellidae: Coleoptera,	
	<i>Oecophylla smaragdina</i> Fab.	Formicidae: Hymenoptera	(45)
	<i>Coccinella transversalis</i> Fabricius.	Coccinellidae: Coleoptera	
2) Bondar's nesting whitefly, <i>Paraleyrodes bondari</i>			
	Chrysopids	Chrysopidae: Neuroptera	(25)
	Coccinellids	Coccinellidae: Coleoptera	
3) Nesting whitefly, <i>Paraleyrodes minei</i>			
	<i>Clitostetus arcuatus</i> Rossi.	Coccinellidae: Coleoptera	(43)
	<i>Serangium parcesetosum</i> Sicard.	Coccinellidae: Coleoptera	
	Coccinellids	Coccinellidae: Coleoptera	
	<i>Dichochrysa</i> spp.	Chrysopidae: Neuroptera	(13)
	Psocids	Psocidae: Psocoptera	
4) Palm infesting whitefly, <i>Aleurotrachelus atratus</i>			
	<i>Dichochrysa astur</i> Banks.	Neuroptera: Chrysopidae	
	<i>Jauravia pallidula</i> Motschulsky.	Coccinellidae: Coleoptera	(14)
	<i>Chilocorus nigrita</i> Fabricius.	Coccinellidae: Coleoptera	
	<i>Cybocephalus</i> spp. Erichson.	Cybocephalidae: Coleoptera	
Parasitoids of invasive whiteflies			
Rugose spiralling whitefly, <i>Aleurodicus rugioperculatus</i>			
	<i>Encarsia guadeloupae</i> Viggiani.	Aphelinidae: Hymenoptera	
	<i>Eloria noyesi</i> Schaus.	Erebidae: Lepidoptera	(95)
	<i>Aleuroctonus vittatus</i> Dozier.	Eulophidae: Hymenoptera	
	<i>Encarsia dispersa</i> Polaszek	Aphelinidae: Hymenoptera	(97)
	<i>Encarsia fernandae</i> Sanchez & Myartseva.	Aphelinidae: Hymenoptera	(108)
2) Nesting whitefly, <i>Paraleyrodes minei</i>			
	<i>Encarsia dominicana</i> Evans.	Aphelinidae: Hymenoptera	
	<i>Encarsia parvella</i> Silvestri.	Aphelinidae: Hymenoptera	(43)
	<i>Encarsia variegata</i> Howard.	Aphelinidae: Hymenoptera	
	<i>Encarsia</i> spp. Foerster.	Aphelinidae: Hymenoptera	(18)
3) Palm infesting whitefly, <i>Aleurotrachelus atratus</i>			
	<i>Eretmocerus cocois</i> Delvare sp	Aphelinidae: Hymenoptera	(109)
	<i>Encarsia basicinta</i>	Aphelinidae: Hymenoptera	
	<i>Encarsia</i> spp. Foerster.	Aphelinidae: Hymenoptera	(110)
	<i>Signiphora</i> spp. Howard.	Signiphoridae: Hymenoptera	
	<i>Encarsia cubensis</i> Gahan.	Aphelinidae: Hymenoptera	(111)

The parasitoid *Encarsia noyesi* was found to effectively reduce whitefly survival, with heavy treatment resulting in less than 10% survival to adulthood (79). Studies on the natural parasitization of *Encarsia guadeloupae* on rugose spiraling whitefly revealed the highest parasitization rate in Kanyakumari district (33.86%) during the study period. The percentage of nymphal parasitization by *E. guadeloupae* was observed in the following order: Kanyakumari (33.86%) > Tirunelveli (17.66%) > Thoothukudi (12.45%) > Tenkasi (11.20%). The highest adult emergence rate of *E. guadeloupae* (21.41%) was recorded in coconut gardens of Kanyakumari, while the lowest was in Tenkasi district (5.37%) (80). The successful introduction of *E. guadeloupae* as a biological control agent demonstrated its effectiveness, particularly when supported by conservation practices (81).

The predatory potential of the chrysopid predator *Pseudomallada astur* against rugose spiraling whitefly was investigated, showing that as larval instars progressed, whitefly egg consumption increased significantly, with first instar larvae consuming 94.75% of 80 eggs (83). Releasing *Apertochrysa astur* at a rate of 600 eggs per palm effectively minimized RSW populations (84). Further exploration of *A. astur* predatory efficiency revealed that third instar grubs could consume up to 333 second instar nymphs of BNW, highlighting their potential as a biological control agent for managing whitefly populations (85).

The third instar grub of *Cryptolaemus montrouzieri* was shown to consume the highest number of whiteflies in the shortest time (11). During their development, grubs of *Chrysoperla zastrowi sillemi* and *Mallada boninensis* consumed an average of 653.6 and 929.8 whiteflies, respectively (46). The predatory capacity of *Menochilus sexmaculatus* was evaluated at different temperatures, with the highest consumption observed at 27±1°C; adult females consumed more prey than males, highlighting the species' adaptability and effectiveness in managing whitefly populations (86). *Nephaspis oculata* was identified as an effective predatory lady beetle for controlling rugose spiraling whitefly, consuming an average of 245.7 eggs before pupation (87).

A 50% mortality rate of whiteflies was achieved using the fungal biocontrol agent *Lecanicillium lecanii*. Botanical controls were also evaluated, with azadirachtin 5% showing the highest mortality rates 66.67% for nymphs and 70% for adults (15). The fungus *Simplicillium lanosoniveum* was characterized and found to be highly virulent against whitefly eggs and nymphs, marking the first recorded instance of this fungus infecting RSW and highlighting its potential as a mycoinsecticide (88).

Two applications of the entomopathogenic fungus *Isaria fumosorosea* significantly reduced whitefly populations in coconut gardens, achieving mortality rates of up to 97.03%. Control efficacy was further enhanced when combined with the parasitoid *Encarsia guadeloupae* (89). *I. fumosorosea* was highlighted as highly effective against whitefly populations, with reductions reaching up to 100%. Additionally, combining the insect growth regulator buprofezin with *I. fumosorosea* demonstrated notable effectiveness in Florida (90). Evaluation of a specific *I. fumosorosea* strain revealed varying mortality rates across different whitefly life stages (91). Among several

bio-pesticides tested, *I. fumosorosea* was found to be the most effective (92), and its combination with chemical insecticides significantly reduced whitefly infestations (93).

A combination of *Isaria fumosorosea* (ICAR-NBAIR Pfu-5) and profenophos significantly reduced rugose spiraling whitefly (RSW) infestations, achieving reductions of 82.97% in infestation levels and 79.68% in mean live colonies. A similar combination with buprofezin also proved effective (92). Various insecticidal treatments were evaluated, with Nitro 505 EC and Bioclean yielding the best results, the latter being highlighted for its eco-friendliness (94). An integrated pest management (IPM) approach tested in Maharashtra demonstrated that neem oil, water sprays, and yellow sticky traps effectively lowered RSW populations (59). Acetamiprid was identified as the most effective treatment, with a rotation strategy involving bio-pesticides like D-Limonene recommended for sustainable management (57). Additionally, soap nut treatments showed high efficacy in controlling RSW, supporting the use of eco-friendly pest management alternatives (59).

The toxicity of methanol extracts from Sweet Flag (*Acorus calamus*) against Bondar's nesting whitefly (*Paraleyrodes bondari*) was evaluated, revealing that mortality rates increased with higher concentrations, reaching 100% at 5%. The LC₅₀ value was determined to be 0.470% at a 0.5% concentration (95). Monitoring whitefly flight patterns was highlighted as crucial for effective pest management. Rugose spiraling whitefly (RSW) activity peaked in the morning, particularly in the Southeast, while Bondar's nesting whitefly (BNW) exhibited a similar preference for that time and location, with minimal evening activity (96).

Conclusion

Invasive whiteflies threaten coconut ecosystems, driven by their wide geographic distribution, adaptability to various host plants and the substantial damage they inflict on coconut palms. By feeding on phloem sap, these pests disrupt the plant's nutrient transport system, resulting in symptoms such as yellowing leaves, premature leaf drop and overall reduced vigour. The rapid spread of whiteflies is facilitated by environmental conditions favouring their proliferation, including warm temperatures and high humidity. Their ability to infest various plant species complicates management efforts, as these pests can easily migrate between hosts. Additionally, the excretion of honeydew by whiteflies leads to the growth of sooty mould, further obstructing photosynthesis and exacerbating the decline in plant health and productivity. Accurate taxonomic identification of the various whitefly species is vital for developing targeted control measures, as different species may exhibit distinct behaviours and vulnerabilities. Identifying invasive whitefly species remains a complex challenge due to their morphological similarities. Therefore, systematic morphological analysis using taxonomic keys, complemented by molecular markers, is crucial for effective pest identification. The increasing prevalence of these invasive whitefly species underscores the urgent need for comprehensive and proactive pest management strategies to safeguard coconut plantations. Combining biological, cultural and chemical control methods within an IPM framework can mitigate whitefly infestations and protect the productivity of coconut palms. Continued research

and collaboration among growers, agricultural experts and researchers will be pivotal in developing innovative solutions to combat the challenges of invasive whiteflies, ultimately fostering resilience within coconut ecosystems.

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Authors' contributions

SS, GP and SV conducted literature searches and data extraction and analyzed and interpreted the compiled information. NB and JS conceptualized the review topic, provided guidance on the review process and approved the final manuscript. GM and AA contributed to manuscript editing, summarization and revision.

Compliance with ethical standards

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