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Exotic whiteflies and Conservation Biological Control in Coconut System

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Abstract. Exotic pests upset biotic balance, threaten biodiversity and distort the livelihood security of the nation. In coconut, five exotic whiteflies *viz.*, spiralling whitefly, *Aleurodicus dispersus* Russell, rugose spiralling whitefly, *Aleurodicus rugioperculatus* Martin, Bondar's nesting whitefly, *Paraleyrodes bondari* Peracchi, non-native nesting whitefly, *Paraleyrodes minei* Iaccarino and palm whitefly, *Aleurotrachelus atratus* Hempel were reported from India. Morphological and molecular identification of these invasive whiteflies were established by puparium and (or) adult taxonomy and cytochrome c oxidase subunit 1 (*COI*) gene, respectively. Co-existence of nesting whiteflies with other exotic whiteflies regulated population explosion and warranted correct diagnosis of whiteflies in coconut system. Weather parameters *viz.*, precipitation, temperature and humidity play an important role in the gradient outbreak of exotic whiteflies. The aphelinid parasitoids (*Encarsia guadeloupae* Viggiani, *Encarsia dispersa* Polaszek), predators (*Apertochrysa* sp., *Cybocephalus* sp. coccinellids *viz.*, *Jauravia pallidula* Motschulsky, *Serangium parcesetosum* Sicard, *Cheilomenes sexmaculata* (Fabricius) and entomopathogenic fungus *Aschersonia* sp. reduced the incursion potential by exotic whiteflies. A sooty mould scavenger beetle, *Leiochrinus nilgirianus* Kaszab (Tenebrionidae: Coleoptera) that devours sooty mould encrusted on palm leaflets during monsoon phase was reported for the first time from Kerala, India. Pesticide holiday approach, conservation biological control using the aphelinid parasitoids, predators and entomopathogenic fungus as well as in situ habitat conservation of *L. nilgirianus* through crop-habitat diversification strategy subdued the invasive potential of exotic whiteflies in coconut system by 60%-80% gaining economic benefit to the tune of 17.59 billion rupees. Strict quarantine and systematic surveillance are the need of the hour to combat the biosecurity risks entering the country.

1. Introduction

Biological invasions, through the routine importation (both accidental and deliberate) of harmful non-native organisms occur frequently and are estimated to cost more than US$100 billion per year worldwide (IUCN 2018). Liberalized international trade, tourism and transport in synergy with changing climate add the inadvertent introduction of pests challenging the natural fauna including defenders and pollinators (Josephrajkumar *et al* 2016). In a short period of four years during 2016-2019, four exotic whiteflies were reported on coconut from India which had in fact threatened native fauna and the production potential of palms (Chandrika Mohan *et al* 2017, Josephrajkumar *et al* 2020a). Whiteflies are confined on the undersurface of palm leaflets predominantly on the older fronds, honeydew deposits occurred on the upper surface leading to sooty mould encrustation which interfered with the photosynthetic efficiency of palms. In India, 476 species of whiteflies under 73 genera have been documented of which eight species from Neotropical origin are found to be invasive pests of quarantine significance (David *et al* 2021). Furthermore, many of these exotic whiteflies co-exist in the same feeding and breeding niche warranting correct diagnosis by experts and extension personnel. Since adult whiteflies are normally intercepted in the field, precise identification of these whiteflies using characteristic features of both adult whiteflies along with puparium are essential. The presence of cryptic species in whiteflies make identification more complex for which molecular characterisation using cytochrome c oxidase subunit 1 (*COI*) gene is found as supporting evidence (Dickey *et al* 2015).

The exotic rugose spiralling whitefly, *Aleurodicus rugioperculatus* Martin (Aleyrodidae: Hemiptera) was reported from Peninsular India for the first time in 2016, has now expanded to all coconut growing belts in Gujarat, Goa, Assam, North-East India, Lakshadweep and Bay Islands in a short period (Chandrika Mohan *et al* 2018; Sundararaj *et al* 2021). Subsequently other exotic whiteflies *viz.*, Bondar's nesting whitefly, *Paraleyrodes bondari* Peracchi, Neotropical nesting whitefly, *Paraleyrodes minei* Iaccarino and palm whitefly *Aleurotrachelus atratus* Hempel are also reported from different coconut growing regions of the country (Josephrajkumar *et al* 2020a, David *et al* 2021).

Weather factors especially precipitation, temperature and relative humidity play a major role in the establishment of *A. rugioperculatus* in a region (Chandrika Mohan *et al* 2017). The abiotic weather extremes dictate the upsurge and establishment of exotic whiteflies in a location at a particular point of time and their inter-relationship with the population dynamics of exotic whiteflies is very important. Due to the expansive mode of spread of these exotic whiteflies and their incursion potential realized in different coconut growing regions, cataloguing and documentation of natural enemies and bioagents involved in the bio-suppression of the exotic whiteflies are very decisive. This is because spraying insecticides in the perennial coconut system is not feasible and is deleterious to natural defenders, scavengers and pollinators which are otherwise involved in biological pest suppression of key pests on coconut (Chandrika Mohan and Sujatha, 2006; Josephrajkumar *et al* 2019b). The exotic spiralling whitefly *Aleurodicus dispersus* Russell introduced in 1993 was effectively subdued by the aphelinid parasitoids, *Encarsia* spp. after the fortuitous introduction of *Encarsia guadeloupae* Viggiani from Lakshadweep Islands in 2000 into the mainland (Ramani *et al* 2002). Henceforth, *A. dispersus* which was causing greater impacts on guava, vegetables and ornamentals had become a minor pest of less economic concern reflecting upon the role of potential natural enemies in the bio-suppression of exotic whiteflies.

Reducing the pestilence of exotic whiteflies on coconut and reviving the palm's health in an eco-friendly manner is of paramount significance. Evolving holistic management packages for exotic whiteflies in the coconut system through nature-protective approaches have become so vital in the changing climate and biodiversity decline that led to the outbreak of exotic whiteflies and subsequently shifted the pest dynamics in coconut (Josephrajkumar *et al* 2020b). Under the circumstances, it becomes so imperative to understand the species composition of whiteflies and defenders, their dynamics during different seasons under varied weather conditions and to develop environmentally responsible approaches to combat them in the perennial coconut system. The objective of the study is to decode the morphological and molecular identity of exotic whiteflies reported on coconut as well as to develop a sustainable pest management strategy to counter the invasion of exotic whiteflies in synergy with natural enemy complex and scavenger beetles in coconut system.

2. Methodology

2.1. Surveillance and morpho-identification

Immature stages of the exotic whitefly complex especially the fourth-instar nymph or puparium as well as the adult whiteflies collected from the coconut system from Peninsular India (Kerala, Tamil Nadu, Karnataka and Andhra Pradesh) are stained and examined by the stereomicroscope LEICA EZ4W and Nikon Eclipse Ni trinocular research microscope as described by Martin *et al* (2000) to confirm the species-level identity. Key diagnostic features on puparium and adult whiteflies are also imaged and compared with different species of whitefly.

The co-existence of different whiteflies in the coconut system especially on diversified intercrops was also identified through the stereomicroscope LEICA EZ4W and the key features confirmed by Nikon Eclipse Ni trinocular research microscope. Whitefly-infested leaf samples of intercrops were systematically observed and the occurrence of different whiteflies in the same feeding niche was documented as photomicrographic images taken through the stereomicroscope.

2.2. Molecular characterization

The genomic DNA of exotic whiteflies was isolated from the adult whiteflies after they were morphologically identified. One to three adult whiteflies of the same species collected in coconut system constituted one lot and were subjected to DNA isolation using a standard protocol. Five exotic whiteflies on coconut (*A. dispersus*, *A. rugioperculatus*, *P. bondari*, *P. minei* and *A. atratus*), areca whitefly, *Aleurocanthus arecae*, citrus whitefly, *Aleurocanthus woglumi*, solanum whitefly, *Aleurotrachelus trachoides* and woolly whitefly, *Aleurothrixus floccosus* were processed for DNA isolation from our laboratory. Primers LCO 14905'-GGTCAACAAATCATAAAGATATTGG-3' HCO 2198:5'-TAAACTTCAGGGTGACCAAAAAATCA-3' (Folmer *et al* 1994) synthesized from Eurofins Genomics India Pvt. Ltd in salt-free status were used for amplification of the mitochondrial cytochrome c oxidase subunit I (*COI*) gene. Polymerase Chain reaction (PCR) was carried out in Techne Flexigene thermal cycler (Sambrook and Russell, 2001). PCR was carried out with an initial denaturation at 95ºC for 5 min followed by 35 cycles of denaturation at 94ºC for 1 min annealing at 55ºC for 1 min and extension at 72°C for 1 min 30 sec. A final extension at 72ºC for 10 min was given for end filling (Josephrajkumar *et al* 2020a). The products were analyzed in 1.0% agarose gel. The amplicons obtained were purified from each reaction mixture using the PCR purification kit from Qiagen. The purified products were sequenced at AgriGenome Labs Pvt. Ltd., Kochi, Kerala.

Partial nucleotide sequences from all processed DNA of the aforesaid whiteflies were deposited in GenBank obtaining appropriate accession numbers. The *COI* nucleotide sequences of different whitefly species used for comparison were retrieved from GenBank (Benson *et al* 1999) including nucleotide sequences deposited from our laboratory as well. BLAST (Altschul *et al* 1990) was used to identify related sequences available in the GenBank database. Multiple sequence alignments were made using ClustalW. The phylogenetic tree was constructed with *COI* gene sequences using Mega X software by the Neighbour-joining method with 1000 replications for bootstrap analysis. Bootstrap values exceeding 50% were kept intact and other sequences were eliminated for drawing the phylogenetic tree. The *COI* gene sequence of *Aphis gossypii* Glover (Hemiptera: Aphididae) voucher DOGR3 (GenBank Acc. No. KR017753.1) was used as the outgroup.

2.3. Correlation with weather factors

The weather data was obtained from the Agricultural Meteorological Station at ICAR- Central Plantation Crops Research Institute, Regional Station, Kayamkulam and correlated with the live whitefly colonies recorded from coconut leaflets using a regression equation. Observations on the incidence of exotic whiteflies on coconut leaflets were recorded at monthly intervals. Five whitefly-infested palms were selected and four leaflets were examined for the occurrence of exotic whiteflies and natural enemies including sooty mould scavenger beetle.

2.4. Bio-suppression of rugose spiralling whitefly

The experiment was conducted at ICAR-Central Plantation Crops Research Institute, Regional Station, Kayamkulam during January-March 2021 on juvenile Kalpasankara (Chowghat Green Dwarf x West Coast Tall) hybrid palms to evaluate the efficacy of biorationals for the bio-suppression of rugose spiralling whitefly. Four treatments were superimposed with ten palms per treatment and sampling were made based on the number of live colonies on four leaflets per palm. The following treatments were included in the experiment

T1 Conservation biological control (No intervention)
T2 Application of entomopathogenic fungus, *Isaria fumosorosea* (5 g /litre)
T3 Application of neem oil 0.5% (5 ml/litre)
T4 Water spray

Two sprays of biorationals were undertaken at fortnightly intervals and observations on the number of live whitefly colonies per leaflet were recorded one month and two months after the superimposition of treatments. Spray fluid was oriented on the undersurface of the selected palm leaflets and about one litre was used for each palm. The total number of pupae on the sampled leaflet and those parasitized by *Encarsia guadeloupae* (based on the blackening of pupae and the presence of a round exit hole) were also counted and expressed as a percentage. The data on colony number was square-root transformed for normalization and the least significant difference of means are separated by Fischer F-test using one-way ANOVA (Gomez and Gomez, 1984).

2.5. Economic benefits of conservation biological control

The monetary value was calculated assuming 300 million palms infested by exotic whiteflies in the country that were unsprayed in the process of conservation biological control. A gain of INR 25/- was realized per palm for not spraying including the cost of chemicals and labour. The cost of the parasitoid, scavenger beetle and pollinator were worked as 10 paise per individual (100 paise equals one INR). A gain of 10% in environmental health was also assumed for overall added value in the assessment of monetary gain. One US$ was worked out to be INR 80/- in the calculation process.

3. Result and Discussion

3.1. Diagnosis

During our surveillance surveys, five different species of exotic whiteflies were observed on coconut palms in all peninsular states of Kerala, Tamil Nadu, Karnataka and Andhra Pradesh. The five exotic whiteflies include spiralling whitefly, *Aleurodicus dispersus* Russell, rugose spiralling whitefly, *Aleurodicus rugioperculatus* Martin, Bondar’s nesting whitefly, *Paraleyrodes bondari* Peracchi, non-native nesting whitefly, *Paraleyrodes minei* Iaccarino and the palm whitefly, *Aleurotrachelus atratus* Hempel (Aleyrodidae: Hemiptera). The diagnostic features of puparium and adult whiteflies of all the exotic whiteflies are briefed below.

3.1.1. Aleurodicus dispersus

Spiral mode of egg-laying encircled with white fluffs, convex puparium with two-tail-like structures, non-corrugated operculum, compound pores absent on VII and VIII abdominal segments possess conical-process, tongue-like lingula with four setae Adult pure-white and size more than 2.00 mm (Figure 1).

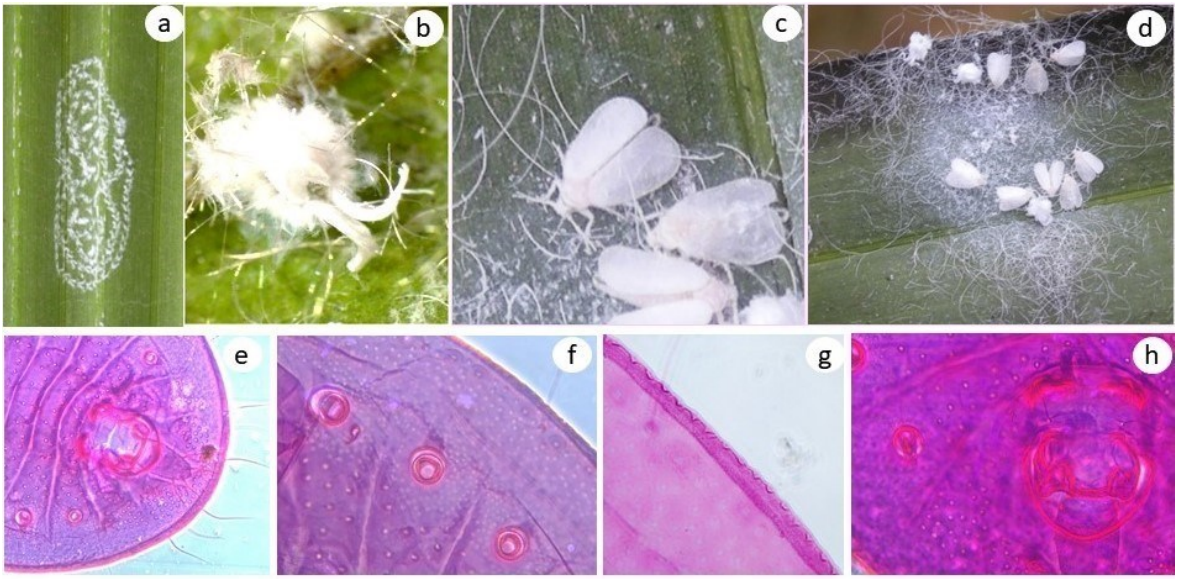

Figure1. Aleurodicus disperses: (a) eggs, (b) puparium. (c) adults, (d) colony, (e) tongue-like lingula, (f) compound pores with no process, (g) marginal crenulation (h) A8 setae

3.1.2. Aleurodicus rugioperculatus

Egg-laying in the spiralling mode that is interrupted and encircled with white fluffs, crawlers have yellowish-patch, convex puparium with a tail-like process, rugose operculum, compound pores present on VII and VIII abdominal segments possess the curved dagger-like conical process, acute and triangular lingula, long parameres with rod-like male aedeagus, the smooth and tubular body of cement gland, an adult with brown mottling on wings and measures more than 2.00 mm (Figure 2).

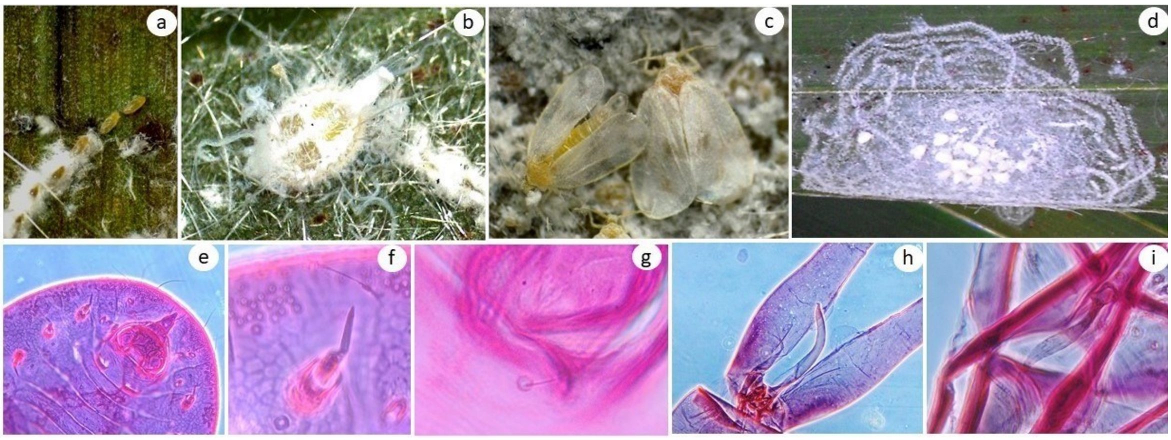

Figure 2. *Aleurodicus rugioperculatus*: (a) eggs, (b), puparia, (c) adults, (d) colony, (e) triangular lingula, (f) compound pore with cone-like process, (g) A8 setae, (h) male genitalia, (i) cement gland

3.1.3. Paraleyrodes bondari

Thickly-woven nest architecture stalked eggs laid at random, flat puparium with sliver strands on the body, four-large and two-small abdominal compound pores, one-large cephalic compound pores, compound pores with conspicuous flower petal structures, discoidal pores distinct near the two small abdominal pores, tongue-like lingula with four setae, parameres pointed at the tip with swollen mid-region, male aedeagus with terminal lips and with posterior and anterior horn-like structures, adult smaller about 1.2 mm with x-shaped marking on the wings (Figure 3).

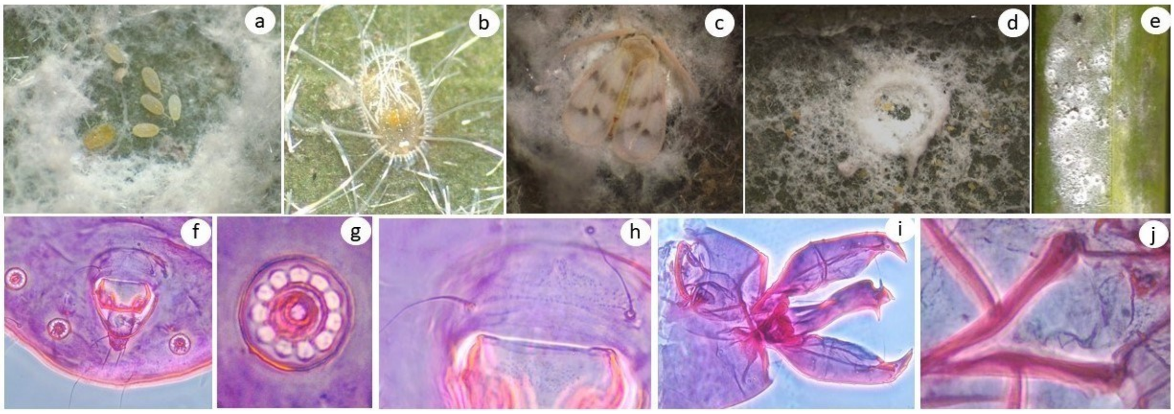

Figure 3. *Paraleyrodes bondari*: (a) eggs, (b) puparium, (c) adult, (d) woolly wax-like nest, (e) colony, (f) vasiform orifice, (g) flower petal-like compound pore, (h) A8 setae, (i) male genitalia, (j) cement gland

3.1.4. *Paraleyrodes minei*

Nest architecture relatively loose, stalked eggs laid at random, flat-puparium with sliver strands on the body, four large and two small abdominal compound pores, one-large cephalic compound pores, compound pores with conspicuous flower petal structures, parameres pointed at the tip with swollen mid-region, male aedeagus with cock-head like structures with short dorsal and long posterior pair of horns. adult smaller about 1.2 mm devoid of any marking and males have ash-coated powdery scales (Figure 4).

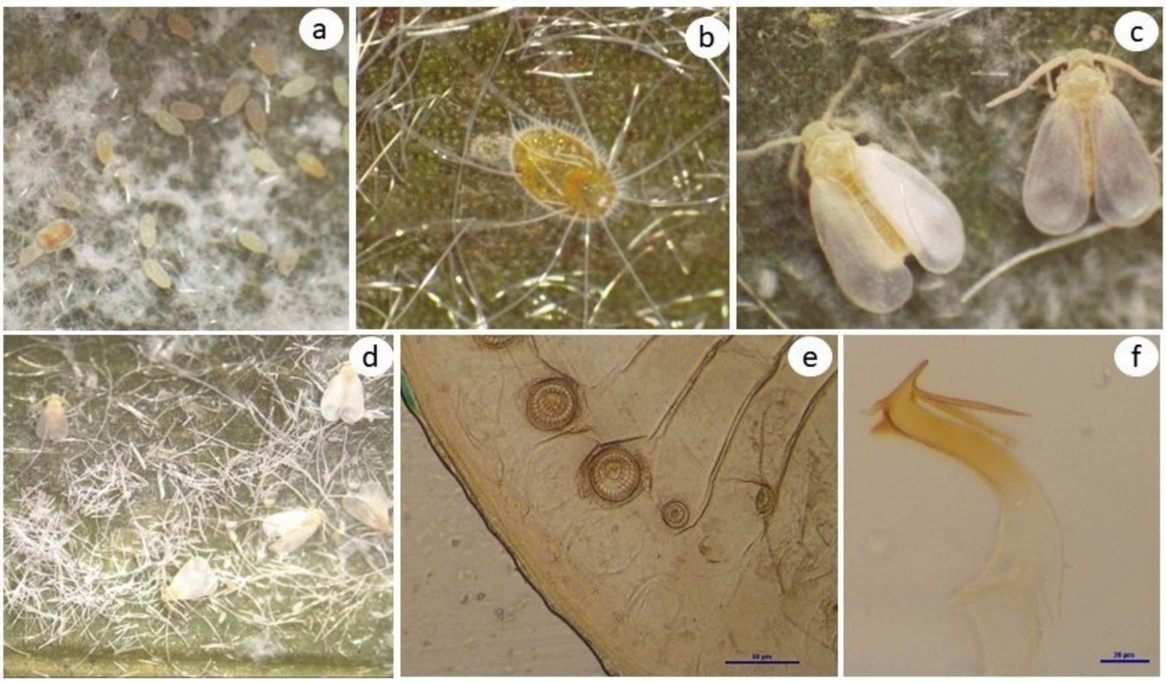

Figure 4. *Paraleyrodes minei*: (a) eggs and crawlers, (b) puparium, (c) adult, (d) colony, (e) pores with flower-petal like, (f) cock-head like aedeagus

3.1.5. *Aleurotrachelus atratus*

Black stalked eggs laid on palm leaflets, early-instar nymphs possess eight white fluffs on dorsum which expand and cover the entire body, aggregation of black puparium visible after adult emergence, lingula round, submarginal fold interrupted at vasiform orifice, adults small longer than broad and wings held roof-like upon rest (Figure 5).

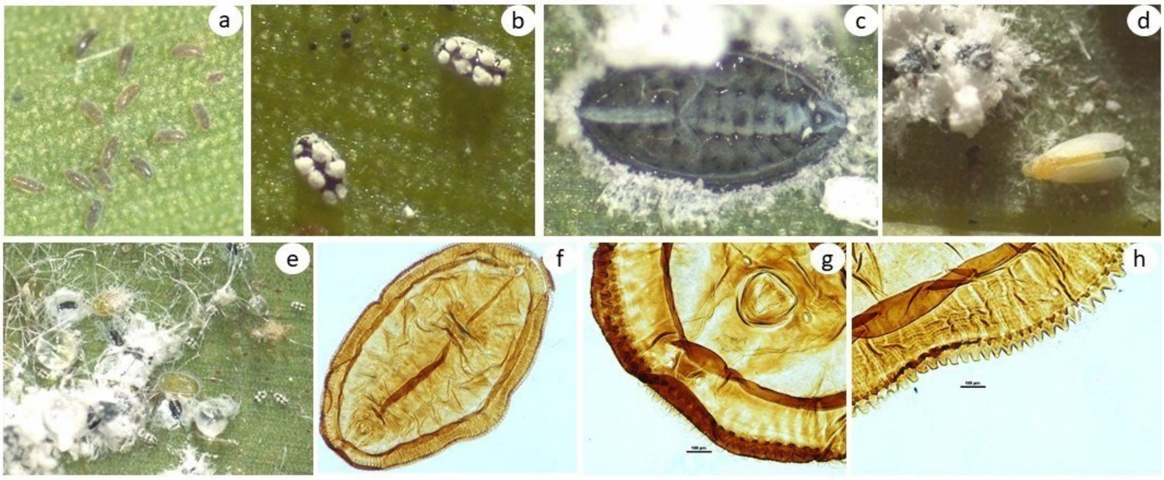

Figure 5. *Aleurotrachelus atratus*: (a) eggs, (b) nymphs, (c) pseudopupa, (d) adult, (e) colony, (f) habitus, (g) vasiform orifice, (h) marginal fold

Based on these characteristic features of puparium and adult whiteflies described, the identity of exotic whiteflies on the coconut system was established. This will serve as a reckoner for extension personal to identify the exotic whiteflies. The identity of the whitefly is also important to document the correct natural enemy associated with it.

3.2. Timeline of exotic whiteflies

Exotic whiteflies are known to the country since 1993. The primary exotic spiralling whitefly, *Aleurodicus dispersus* was reported as a minor pest on coconut in 1996 (Prathapan 1996). Fortunately, it never assumed a pest status due to non-preference and fortuitous introduction of aphelinid parasitoids, *Encarsia* spp. from Lakshadweep Island in 2000 (Ramani *et al* 2002). However, in a span of four years (2016-2019), four exotic whiteflies from the Neotropical region emerged into Peninsular India, impeding the production potential of palms. The exotic rugose spiralling whitefly (RSW) [*Aleurodicus rugioperculatus*] reported first on coconut from Palakkad (Kerala) and Pollachi (Tamil Nadu) in 2016 remains a key pest on coconut in isolated pockets of favourable weather factors (Shanas *et al* 2016, Sundararaj and Selvaraj 2017, Chandrika Mohan *et al* 2017, David *et al* 2021). It is also found as a major pest on oil palm and a minor pest on bananas in certain coconut-growing belts.

During 2018, two nesting whiteflies *viz.*, Bondar's nesting whitefly (*Paraleyrodes bondari*) and non-native nesting whitefly (*Paraleyrodes minei*) co-existed in the colonies of RSW and were reported from Kerala, Tamil Nadu and Andhra Pradesh (Josephrajkumar *et al* 2019a, Chandrika Mohan *et al* 2019, David *et al* 2021). Nesting whiteflies were relatively smaller (1.00 mm) with X-shaped markings on the wings of *P. bondari*, whereas RSW is about 2.20 mm in size with conspicuous brown mottling on wings. Being smaller in size, honeydew produced by nesting whiteflies was relatively lower than RSW. Also, the nymphal stages of nesting whiteflies are flat while it is convex for RSW (Josephrajkumar *et al* 2019a, Chandrika Mohan *et al* 2019). In addition, a neotropical palm whitefly (*Aleurotrachelus atratus*) was recently reported on coconut from Mandya and Mysuru district of Karnataka in 2019 (Selvaraj *et al* 2019, Josephrajkumar *et al* 2020a, David *et al* 2021) and recently from Tamil Nadu and Kerala (Jilu *et al* 2022). Nesting whiteflies are invariably found associated with other exotic whiteflies, justifying the need for accurate diagnosis of exotic whiteflies and the natural enemies associated.

3.3. Co-existence of invasive whiteflies

According to Gause's principle, no two organisms could occupy the same niche for survival, however, different species of whiteflies co-occurred in the coconut system. In Mandya, Karnataka we found the co-existence of non-native nesting whitefly (*P. minei*) with palm whitefly (*A. atratus*). Similarly, Bondar's nesting whitefly, *P. bondari* was found to co-occur with solanum whitefly (*A. trachoides*), areca whitefly (*A. arecae*), citrus blackfly (*A. woglumi*) and rugose spiralling whitefly (*A. rugioperculatus*) [Figure 6]. Co-habitation of two spiralling whiteflies and nesting whiteflies was reported on guava as well (Josephrajkumar *et al* 2020a). Co-existence of exotic whiteflies *viz.*, *A. rugioperculatus*, *P. bondari* and *P. minei* was observed on arecanut leaflets in association with the native areca whitefly, *A. arecae* for the first time in 2020 (Thube *et al* 2020). In certain cases, competitive regulation of RSW by nesting whiteflies could be observed making co-existence as an ecological determinant factor in regulating the population dynamics of a pest. In the same niche, the nesting whiteflies compete and breed within the colony of spiralling whiteflies and regulate the population enhancement of the latter.

Figure 6. Co-existence of exotic whiteflies: (a) *P. minei* and *A. Atratus*, (b) *P. bondari* and *A. woglumi*, (c) *P. bondari* and *A. rugioperculatus*, (d) *P. bondari* and *A. arecae*, (e) *P. bondari* and *A. trachoides*, (f) *P. bondari* and *Aleuroclava canangae*

3.4. Molecular identification

Presence of cryptic species in whiteflies warranted molecular characterization for establishing correct identity. Evolutionary lineage and homogeneity of each genus could also be ascertained by the phylogenetic tree and for the precise identification of whiteflies. The phylogenetic tree of closely related exotic whiteflies in the coconut system was presented in Figure 7. It was found that five exotic whiteflies of coconut belonged to two taxonomically distinct subfamilies, Aleurodicinae (*Aleurodicus* spp., *Paraleyrodes* spp.) and Aleyrodinae (*Aleurotrachelus* spp.) and highlighted their evolutionary lineage. Molecular phylogenetic analysis also indicated the relative affinities of the five whitefly species. There were three phylogenetic clades in which the exotic whitefly species complex infesting coconut could converge *viz.*, *Aleurodicus*, *Paraleyrodes* and *Aleurotrachelus* groups. The first two groups are intrinsically related than *Aleurotrachelus* group, which is distantly placed from the other two. The native areca whitefly, *Aleurocanthus arecae* was found closely linked with *Aleurotrachelus* group and forms a sub-clade with other Aleurocanthus spp. Here again, *Aleurotrachelus trachoides* was found to be closely interrelated with *Aleurotrachelus atratus* than to *Aleurothrixus floccosus* as corroborated previously by Josephrajkumar *et al* (2022a). Furthermore, *Bemisia tabaci* is found closely related to *Aleurotrachelus* group as a member of Aleyrodinae than that of *Paraleyrodes* and *Aleurodicus* groups (Figure 7). *Paraleyrodes pseudonaranjae* was closely associated with *Paraleyrodes bondari* than *Paraleyrodes minei* and genetically widened from that of *Aleurodicus* group with more affiliation towards *Paraleyrodes* group. Thus, the genetic relatedness of exotic whiteflies on coconut was clearly depicted which also forms supportive evidence in case of the occurrence of cryptic species. The study also indicated the absence of cryptic species on exotic whiteflies infesting coconut.

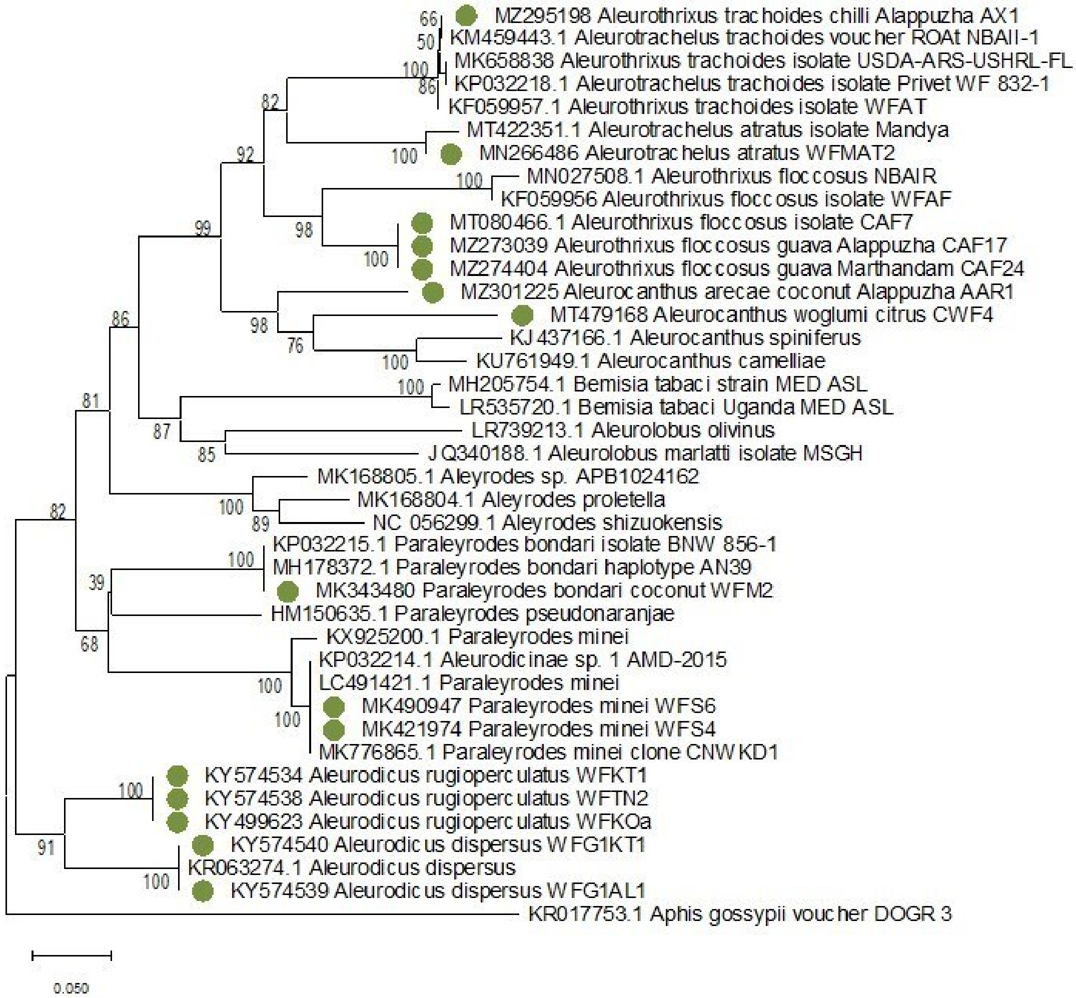

Figure 7. Phylogenetic tree of closely related exotic whiteflies

3.5. Influence of weather factors on whitefly population

Weather plays an important role in the population dynamics of whitefly population and in general whiteflies are more susceptible to wetness (Chandrika Mohan *et al* 2017).

Together with bioagents, the outbreak of exotic whiteflies in a region is determined by the modulation of weather parameters. The maximum temperature, relative humidity, rainfall and the difference between maximum and minimum temperature was correlated with RSW population and presented in Figure 8. The population of RSW was found to be positively correlated with maximum temperature (r=0.89) and difference in temperature (r=0.71), whereas, a negative correlation was observed with relatively humidity (r=-0.69) and rainfall (r=-0.49). Thus, both weather factors and parasitic potential of the aphelinid parasitoid, *E. guadeloupae* play a critical role in the population dynamics of RSW.

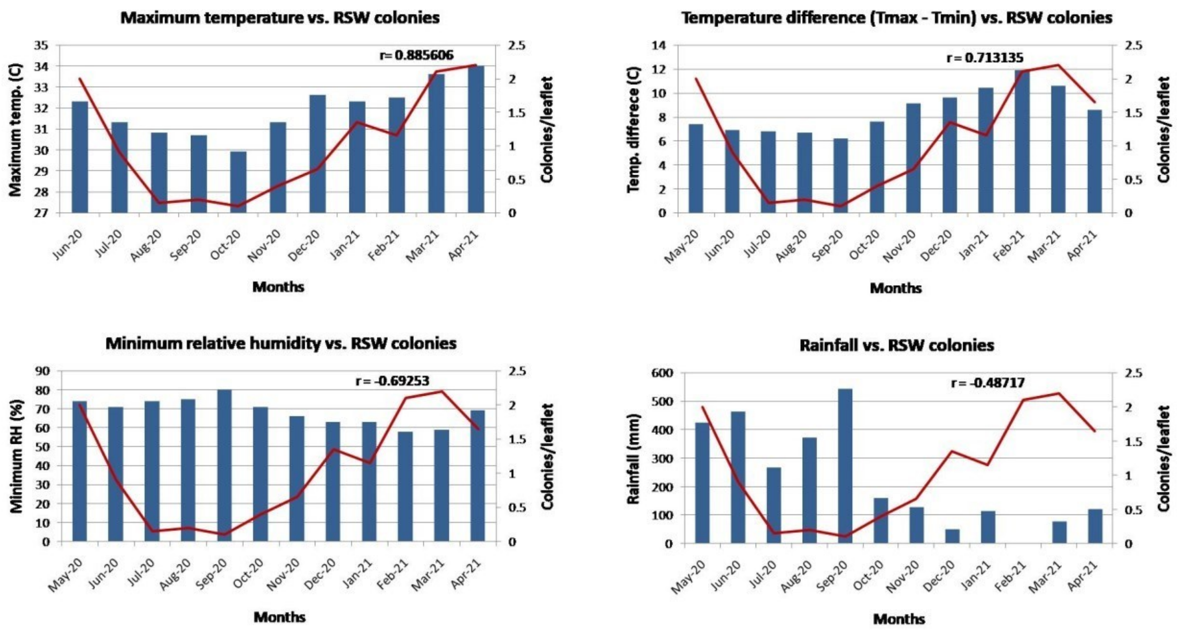

Figure 8. Weather factors versus RSW population

3.6. Biological suppression of rugose spiralling whitefly

In order to evolve a holistic management strategy for exotic whiteflies, a field experiment was conducted using biorationals and conservation biological control during January-March 2021 for the bio-suppression of rugose spiralling whitefly in the coconut garden. The experiment was conducted during the peak population of RSW coinciding summer period. The results are presented in Table 1.

Table 1. Bio-suppression of rugose spiralling whitefly

Treatments	RSW population (No. of live colonies /leaflet)					Parasitism (%)
	Pre-treatment	After one month	Reduction (%)	After two months	Reduction (%)	
Conservation biological control	0.78 (1.33)	0.73 (1.29)^{ab}	6.41	0.30 (1.13)	61.5	58.8
Isaria fumosorosea	0.98 (1.26)	0.95 (1.37)^{a}	3.06	0.62 (1.20)	36.7	46.8
Neem	0.85 (1.30)	0.18 (1.08)^{b}	78.8	0.15 (1.07)	82.4	45.9
Water spray	0.53 (1.20)	0.18 (1.07)^{b}	66.0	0.28 (1.12)	47.2	54.3
CD (P=0.05)	ns	0.217		ns		ns

Under good nutrition management, it was found that palms treated with neem oil (0.5%), water spray and conservation biological control could reduce the RSW population significantly ranging from 0.18-0.73. Palms sprayed with *Isaria fumosorosea* registered the highest RSW population (0.95) after one month of treatment. However, after two months all treatments were found on par indicating the importance of the pesticide holiday approach and conservation biological control in the biological pest suppression of RSW with higher parasitism (58.8%) by *E. guadeloupae*. The least reduction was observed on palms exposed to *Isaria fumosorosea* (36.7%), whereas, neem oil-treated palms registered the highest pest reduction of 82.4%. Good health management practices coupled with ecological intensification through crop-pluralism are very much important in recouping palm health and also reducing the pest impact by stimulo-deterrance. Coconut-based crop-pluralistic orchards have reduced whitefly attacks due to diversified volatile cues than monocropping system (Josephrajkumar *et al* 2018b, Josephrajkumar *et al* 2020b, Josephrajkumar *et al* 2022b).

3.7. Conservation biological control

Non-chemical approach favouring the conservation biological control using the aphelinid parasitoid, *Encarsia guadeloupae* and the chrysopid predator, *Apertochrysa* sp., coccinellids *viz.*, *Jauravia pallidula* Motschulsky, *Serangium parcesetosum* Sicard, *Cheilomenes sexmaculata* (Fabricius), cybocephalids as well as in situ preservation of the sooty mould scavenger beetle, *Leiochrinus nilgirianus* Kaszab were found pivotal in the bio-suppression of the exotic whiteflies (Chandrika Mohan *et al* 2017, Josephrajkumar *et al* 2019b, Josephrajkumar *et al* 2020b, David *et al* 2021). The economic benefits of conservation biological control realized in 300 million palms in the country are presented in Table 2.

Table 2. Ecological benefit outcome realized in conservation biological control of RSW

Ecological benefit outcome	Gain (Billion Rupees) INR	Million US$
Non-spraying of insecticides for at least 300 million palms @ Rs 25/palm	7.500	94
E. guadeloupae conserved 500 nymphs or pupae of RSW /palm and 40% parasitism (200 x 300 million) @ 10 paise per parasitoid	6.000	75
L. nilgirianus conserved @ 10 per palm for 180 million palms @ 10 paise per scavenger beetle	0.180	3
Pollinators (Bees, ants, weevils etc.) conserved @ 100 per palm from at least 300 million palms @ 10 paise per pollinator	3.000	37
Ecosystem services and environmental health 10% of the value of defenders /pollinators	0.918	11
Total	17.598	220

Table 2 highlighted an ecological service outcome to the tune of 17.59 billion rupees (INR) realized in the conservation biological control approach just by avoiding insecticide spray and safeguarding the environment. Conservation biological control was mainly preferred in the coconut system to conserve the pollinators, natural defenders and bio-scavenger beetles which were actively involved in the regulation of *A. rugioperculatus* and serve as excellent ecological service providers (Josephrajkumar *et al* 2019b, Josephrajkumar *et al* 2020b).

Chemical application in the perennial coconut system is not feasible and cannot be implemented as well due to the ill effects of pesticides on natural enemies and the environment. Water bodies adjacent to coconut orchards are found to be more sensitive to chemicals, affecting aquatic organisms. Thus, zero tolerance to chemicals conserved the natural enemies and scavenger beetles in Kerala, India. It was also observed that the chrysopid predator, *Apertochrysa* sp. coccinellid beetles, cybocephalids and the aphelinid parasitoid, *E. guadeloupae* co-occurred along with the pest and in a period of four to five months, these natural enemies subdued the pestilence potential of RSW. Parasitism which was initially found to be 10%-15% rose to as high as 70%-80% in a period of five to eight months (Chandrika Mohan *et al* 2017, Josephrajkumar *et al* 2019b, Josephrajkumar *et al* 2020b). Such an approach of a natural and ecologically safe method of whitefly management enhanced ecosystem services in the coconut system. It also delivered the twin benefits of environmental security and human safety experienced in the long run for sustainable whitefly management.

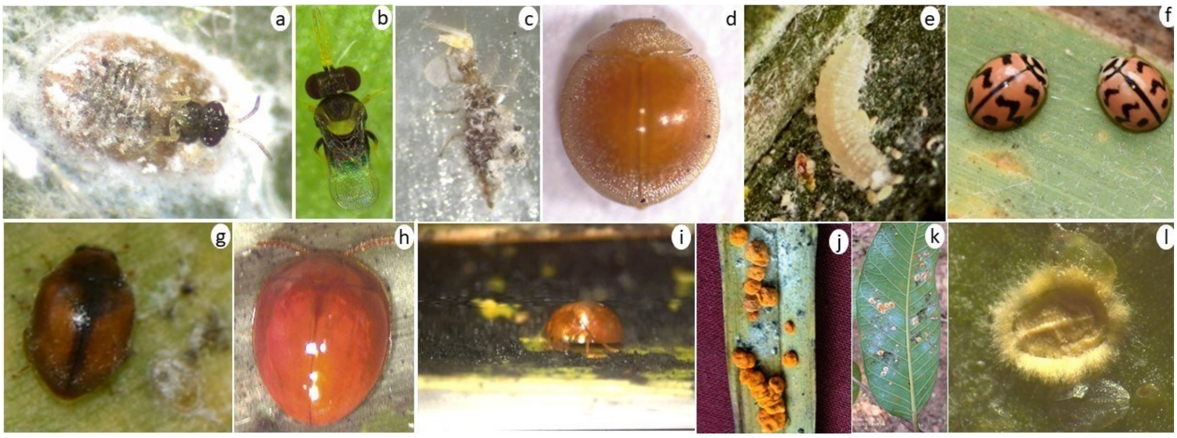

Figure 9. Conservation biological control of exotic whiteflies on coconut: (a) *Encarsia guadeloupae* emerging from puparium of RSW, (b) *Encarsia guadeloupae*, (c) *Apertochrysa* sp., (d) *Jauravia pallidula*, (e) *Cybocephalus* sp., (f) *Menochilus sexmaculatus*, (g) *Scymnus nubilis*, (h) *Leiochrinus nilgirianus*, (i) *L. nilgirianus* feeding on sooty mould, (j) & (k) *Aschersonia* sp., (l) unidentified

In addition, during the monsoon phase the sooty mould scavenger beetle, *L. nilgirianus* devoured the sooty mould encrusted on palm leaflets and completely cleansed the palms reviving back the photosynthetic efficacy in toto (Josephrajkumar *et al* 2018a). Random occurrence of the entomopathogenic fungus, *Aschersonia* sp. infecting the whitefly population was also recorded in those gardens free from a chemical application (Jilu *et al* 2022). Accordingly, the invasive potential of RSW was subdued by the natural enemies (*E. guadeloupae*, *Apertochrysa* sp., *Cybocephalus* sp., coccinellids) and bio-scavenger beetle (*L. nilgirianus*) restoring the natural ecosystem and the dynamic pollinators involved in ecological services (Fig. 9). In this conservation agriculture approach, the RSW population got reduced by 80% and parasitism reached as high as 85% in a period of five to six months (Chandrika Mohan *et al* 2017, Josephrajkumar *et al* 2019b, Josephrajkumar *et al* 2020b).

Furthermore, two entomopathogenic fungi *viz.*, *Isaria fumosorosea* and *Simplicillium lanosoniveum* were found associated with RSW and were used in the bio-suppression of the pest (Sundararaj *et al* 2021). The ecological intensification strategy with crop habitat diversification in a coconut plantation could disorient pests and favour the habitat for defenders, scavengers and pollinators making the system holistic and pest-regressive (Josephrajkumar *et al* 2018b, Josephrajkumar *et al* 2020b). Thus, the correct identification of exotic whiteflies led to the accurate identification of their natural enemies so that an effective biocontrol strategy is evolved through the ecological intensification process to suppress exotic whiteflies on coconut.

4. Conclusion

The study highlighted the morphological and molecular identification of exotic whiteflies in the coconut system, which are based on puparium and adult features of whiteflies. Nucleotide sequences of exotic whiteflies on coconut and their genetic relatedness with other whiteflies were established. The co-existence of different whiteflies in the same niche developed competitive regulation of whiteflies and at the same time emphasised on the correct diagnosis of whiteflies. Weather factors especially precipitation, temperature and humidity are major drivers in the population dynamics of whiteflies. Pesticide holiday approach and conservation biological control using the aphelinid parasitoids, predators such as chrysopids, cybocephalids and coccinellids and *in situ* habitat conservation of sooty mould scavenger beetles are found effective in the bio-suppression of exotic whiteflies on coconut realizing a monetary gain of 17.59 billion rupees in the country. Good palm health management and ecological intensification through crop pluralism disorient whiteflies and de-risk farmers realizing sustainable income with reduced whitefly incursion.

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