

BIOLOGICAL ATTRIBUTES OF RUGOSE SPIRALLING WHITEFLY, *Aleurodicus rugioperculatus* MARTIN ON OIL PALM AND KEY HOSTS: IMPLICATIONS FOR PEST MANAGEMENT

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ABSTRACT

Since its introduction in 2016, the invasive whitefly species, rugose spiralling whitefly (RSW), *Aleurodicus rugioperculatus* Martin has become a key pest of oil palm in India; However, the infestation is severe in coconut. This study, for the first time, revealed the biological attributes of RSW on oil palm recording a developmental period (egg to adult) of 38 ± 2.36 days. The total life cycle (including adult survival) was 56.73 ± 2.87 days. Morphometric traits were similar for oil palm and coconut, except in the 4th instar and male adult. Comparative survival of RSW life stages revealed maximum mortality during adult eclosion on all studied hosts. Post hoc comparisons showed that adult emergence was highest on custard apple (0.978 ± 0.06) and ramphal (0.962 ± 0.07), followed by guava (0.872 ± 0.10). Coconut (0.707 ± 0.12) and oil palm (0.765 ± 0.13) showed lower emergence rates. Field observations across eight hosts recorded the lowest adult emergence (8.4 ± 2.6) in oil palm. Overall, oil palm was a medium-preferred host after coconut while guava, custard apple and ramphal were highly preferred. The practical applications of these findings in the ecological engineering of oil palm plantation for sustainable management of RSW are discussed.

Keywords: biology, host, morphometrics, oil palm, rugose spiralling whitefly.

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INTRODUCTION

Oil palm is the highest oil yielding perennial crop with a production of 4–5 t of palm oil ha⁻¹. The cultivation of oil palm is remunerative, as with the best management practices, farmers can get a yield of 20–25 tons per hectares of fresh fruit bunches (FFBs) for a minimum of 25–30 years. Both FFB and oil yields are around five times the yield of traditionally grown edible oils and that too without any serious impact on the environment, thereby providing stable income to the growers. Moreover, palm oil is in a prime position with respect to consumption and global oil trade (Statista Research Department, 2025), accounting for approximately 40% of global edible oil demand. The cultivation of oil palm assumes significance in India to achieve

self-sufficiency in edible oils. In India, oil palm is presently grown in 0.473 million hectares covering 15 states with its major area in the state of Andhra Pradesh (0.229 million hectares).

Whiteflies are the most promising noxious insect pests attacking a variety of crops around the world (Van Lenteren & Noldus, 1990). Plant trade among countries, miniature size, cryptic nature, strong attachment to plant parts, among other factors, make whiteflies the most commonly invading pest species to new geographical areas (Sundararaj et al., 2021). Rugose spiralling whitefly (RSW), *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae) is one among them, infesting especially coconut in 22 countries (Francis et al., 2016). Although the first report of the species dates back to 2004 from Belize (Central America) on coconut (Martin, 2004), RSW was first reported in India during 2016 in Pollachi, Tamil Nadu on coconut (Srinivasan et al., 2016; Sundararaj & Selvaraj, 2017). During the same year, RSW was also observed in coconut plantations

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in Andhra Pradesh (Chalapathi Rao et al., 2018), a state of India that tops in area under oil palm cultivation. In the state, after coconut, oil palm is the most affected host (Selvaraj et al., 2019), with an estimated affected area of 0.135 million hectares of coconut and oil palm (Selvaraj et al., 2024). The incidence of RSW on oil palm is seasonal in India, especially due to the existence of clear cyclic seasons (summer, winter and rainy seasons). Although the pest is seen throughout the year, the population buildup starts from the commencement of winter (November to December) and continues throughout summer (until May), which is generally considered a no-rain period. However, any intermittent summer showers or cyclonic rains during this period wash away the pest, thereby reducing the negative impact on host plants. Moreover, the population buildup of whiteflies in any given year or season first appears on coconut, which ultimately infests oil palm, as there is mixed or integrated farming of coconut, oil palm and other fruit crops (guava, custard apple, and other host plants, which are also hosts of RSW) in the study area (Andhra Pradesh, India). So, in any given year RSW can be considered a biotic stress to oil palm only for around 3–4 months based on the pest population.

All the life stages of RSW are seen congregated as colonies, mostly on the abaxial surface of leaves or leaflets in all the hosts (although random egg laying is also reported on adaxial surfaces, frond bases and developing fruits). Egg laying by a gravid female occurs in a spiralling pattern trailed by waxy filaments. The randomly laid eggs within the patterns are also covered with a waxy coating for protection from the external environment. For that matter, except for the newly hatched and moulted instars, all the stages of the insect are covered with thin waxy filaments as a protective covering. Newly hatched first instars move a little distance (in mm) from the egg within the colony and settle to suck the leaf sap. During development, the nymphal instars moult four times to become adults, which are also seen congregated within the colony. The females after mating, fly to adjacent leaves for egg laying. The adults come back to the same colony by the end of the day (Selvaraj, 2019; Taravati & Mannion, 2014). Above all, not much is known about the clear biological attributes of RSW on oil palm in comparison with other hosts.

RSW is highly polyphagous with 96 hosts recorded from Florida alone (Stocks & Hodges, 2012). In India, the infestation is seen on coconut, oil palm (Selvaraj et al., 2019; Sundararaj & Selvaraj, 2017), banana, guava (Selvaraj et al., 2017), mango (Chalapathi Rao et al., 2018), sugarcane (Pradhan et al., 2022), as well as many other ornamental and fruit crops depending on the locally grown or available flora. Some compilations reported a host span of more than 120 species covering 43 families

of the plant kingdom (Francis et al., 2016; Karthick et al., 2018). It is also important to note that, not all the plant species reported in the host range may support the full biology of the pest. So, only a fraction of hosts are considered 'true hosts' which support the potential biological survival and rapid development, which is evident by the live colonies with maximum numbers of surviving nymphs and adults. The biological fitness of whiteflies on a given host is a function of specific host traits, viz. the physical leaf structure (e.g., pubescence, epidermal structure) and physiological and chemical profiles (both constitutive and induced defensive or nutritional elements) (Inbar & Gerling, 2008). In view of this, the present study investigated whether oil palm is a good host in comparison with coconut and other fruit crops. Moreover, studying the biology of RSW on any given host helps in understanding the relationships at trophic levels (including natural enemies) and designing best management tactics (Taravathi & Mannion, 2016). Comparative survival statistics of RSW on different hosts are also scarce, and this aspect was investigated in the present study. Moreover, different biological attributes and survival statistics of RSW on native host species especially coconut and oil palm are compared. This comparative biology on RSW yielded some interesting insights into the survival, behavioural biology and preferences of RSW on different hosts. The applications of these differences in designing an integrated pest management for RSW are also discussed. The oil palm's perennial characteristics and extensive cultivation area especially in Andhra Pradesh, India, indicate that even a "medium-preferred" host status carries significant pest ramifications.

MATERIALS AND METHODS

Test Insect

The culture of RSW was established on two-year-old potted nursery plants of oil palm (72 *dura* × 74 *pisifera*, a commonly used tenera hybrid) and coconut (variety: East coast tall) from naturally infected leaflets under field conditions. The plants were kept under a shade net and the culture was continuously propagated on respective hosts since January, 2022 with no stress in respect to insecticides, natural enemies and biocontrol agents.

Studies on Biology and Morphometry of Life Stages of RSW

The studies were conducted on potted one-year-old oil palm and coconut seedlings

kept in the nursery area of the ICAR-Indian Institute of Oil Palm Research (IIOPR), Pedavegi (16° 48' 36" N, 81° 07' 48" E) during November to December, 2024. A total of three hosts palms were enclosed in a net cage along with an RSW-infested palm with adults to allow egg laying. Both oil palm and coconut plants are kept separately in cages along with their respective infested host plant. The palms are monitored daily for identification of fresh egg laying by adults (spirals), which were tagged for the date and time of egg laying and brought out of the cages for further observations on biology and morphometry of different life stages. The RSW-infested coconut and oil palm palms are maintained separately by using a mosquito net as a partition. The morphometrics of each stage of development are documented from detached leaves using a ZEISS stereozoom microscope, Stemi 305 (Carl Zeiss Microscopy GmbH, Germany) with an image documentation system, ZEISS AxioCam 208 colour (Carl Zeiss Microscopy GmbH, Germany) assisted by an on-screen display for standalone ZEN v3.0. The time periods of development viz., egg period, different instar periods and adult longevity are also recorded. For this, field-identified colonies were tagged and observed by taking a photograph using a macro lens (100 mm Tokina), which was zoomed to identify the developmental stages, especially for egg, 1st and 2nd instars. The morphometry of each development stage (egg, nymphs and adults) was estimated from 30 randomly selected individuals on the next day of ecdysis or eclosion from different colonies reared on detached leaves under laboratory conditions. Whereas, estimation of time periods of each stage was done from 15 colonies each starting from 10 eggs by carefully removing remaining eggs from the colony using a camel hair brush.

Studies on Survival of Different Developmental Stages of RSW

The stagewise development and survival numbers of RSW are estimated from five hosts viz., oil palm, coconut, guava, ramphal and custard apple in open conditions in the fruit garden of ICAR-IIOPR, Pedavegi. For each host, three freshly laid colonies were identified and tagged with the date of egg laying. The 1st instar is not actively mobile and settles for the rest of the development within the waxy egg spiral made by the adult. Upon observation of this behaviour, in each tagged colony, 30 eggs are allowed to develop further by careful removal of other eggs using a camel hair brush and a handheld pocket microscope. These 30 eggs per colony were observed for their further development and the numbers remaining in each developmental stage are counted. The number of surviving individuals in each stage is averaged

across three colonies per host and presented. Care has been taken to avoid any incidence of natural enemies and diseased colonies if any, for data collection.

Morphometric Variation in 4th Instar and Males of RSW

The study on morphometry of RSW on oil palm and coconut showed a significant variation only in the measurements of the 4th instar and adult male. Keeping this in view, a study on the morphometry of these life stages was attempted from other preferred hosts viz., guava, custard apple and ramphal (Jamaican apple, *Annona reticulata*). A total of 15 individuals of targeted stages of RSW were randomly selected from infected hosts, brought to the laboratory, and morphometrics were done as detailed above.

Studies on RSW Colonies Under Field Conditions

To estimate the variations in colony morphometry and number of life stages per colony a field observation study was conducted on locally available major hosts harbouring RSW viz., oil palm, coconut, guava, jackfruit, jamun (malabar plum), avocado, mango, ramphal (*Annona reticulata* or sour sop). Three plants belonging to the same variety from the Fruit Garden established at ICAR-IIOPR, Pedavegi are selected for data collection. All the palms are planted at different years, with an age of around 5–10 yr. A total of three palms per host species and 10 colonies per palm at different stages of development (totalling 30 colonies per stage), i.e., colonies with eggs, colonies with 4th-stage nymphal instars, and colonies with adults, are selected for data collection. The egg stage colonies are measured for their length and width of the spiralling pattern made by the adult RSW during egg laying. The same colony, along with the leaflet, was brought to the laboratory and studied for the number of eggs per colony after careful removal of the waxy coating using a camel hair brush. Similarly, colonies with 4th-stage nymphal instars and adults were counted for their number per colony. The number of adults per colony was estimated from the newly hatched ones and during the late hours of the day, i.e., after 7.00 am to ensure the presence of all the adults. This data collection was done in December 2023. During the study, the pattern of occurrence of adults and nymphs was also documented to observe any variations amongst the hosts.

Data Analysis

The data on morphometrics and survival counts of life stages both in laboratory and field conditions

were analysed using analysis of variance (ANOVA) to compare mean values in two-way analysis using the least significant difference test (LSD) at $p < 0.05$. Stage-specific survival was analysed using binomial GLMMs (logit link), with Host (five levels) as a fixed effect and Colony (Replication) as a random intercept. For each stage, the response was the number surviving out of those entering that stage (aggregated binomial). Likelihood-ratio χ^2 tests evaluated host effects. Estimated marginal means (EMMeans) with 95% CIs were reported on the response scale. Tukey's adjustment was used for the post-hoc pairwise comparisons among hosts. A simple correlation analysis was also performed using colony dimensions and the number of egg and nymphal stages. All data analyses were performed using an online version of grapesAgri1 (Gopinath et al., 2021).

RESULTS AND DISCUSSION

The invasion of RSW in India over wide and varied geographies and on a variety of horticulture crops occurred in a short span of time between 2017 and 2020 (Chalapathi Rao et al., 2018; Sundararaj et al., 2021). This is chiefly attributed to the species' ability to exploit a wide range of locally available host plants (Nandhini & Srinivasan, 2023), which is supported by multispecies cropping systems. Moreover, the major host plants (coconut, oil palm, banana and other perennial crops) are perennials which allow pest perpetuation, even under effective management conditions due to a residual populations whose recurrence is inevitable. Under such instances, relying on ecological engineering of the plantation allows continuous pest suppression (Josephraj Kumar et al., 2022; Logeshkumar et al., 2024) with minimal plant protection intervention

(Josephraj Kumar et al., 2022). In such instances, a thorough knowledge of pest biology on possible host plants helps in designing ecological pest suppression tactics. In Andhra Pradesh (especially in the study area which is dominated by oil palm), as there is mixed cropping of coconut and oil palm (as an intercrop or border crop), RSW infestation and spread become severe on oil palm in no time (Selvaraj et al., 2019), as there is always a migration of pests from coconut to oil palm (Kalidas, 2012). However, the biological attributes of RSW on oil palm are considered inferior in comparison to coconut, as the latter is the most preferred host. Moreover, in any given season, the first and severe occurrence of the pest was observed on coconut, followed by oil palm. So, to understand the ordeal in pest biology on oil palm in comparison with coconut and other hosts, the present study was attempted for the first time.

The dimensions of different life stages of RSW on coconut and oil palm were highly similar except for the width of the 4th instar and the adult male (Table 1). Similarly, a significant and large difference was also observed in the last-stage instars of *Trialeurodes ricini* when grown on different hosts (Huang et al., 2014). Although the difference is minimal in the case of the 4th instar, the male on oil palm is much bigger than the male on coconut which accounts for nearly double the size. Whereas, there is no significant difference in the case of females. The average length and width of nymphal instars of RSW on oil palm were in partial agreement with the study by Saneera et al. (2023). The dimensions of instars have a significant impact on their parasitisation by parasitoids. *Encarsia guadeloupae*, a naturally occurring Aphelinidae parasitoid of RSW, effectively parasitises only second and third instars (Mollot et al., 2015; Saranya et al., 2021a).

TABLE 1. MORPHOMETRICS OF LIFE STAGES OF RUGOSE SPIRALLING WHITEFLY (RSW) ON OIL PALM AND COCONUT

Life stages	Length (mm)		Width (mm)	
	Coconut	Oil palm	Coconut	Oil palm
Egg	0.32 ± 0.02 ^h	0.32 ± 0.02 ^{gh}	0.14 ± 0.01 ^h	0.13 ± 0.01 ^h
1st Instar	0.37 ± 0.01 ^g	0.35 ± 0.06 ^{gh}	0.19 ± 0.01 ^g	0.19 ± 0.01 ^g
2nd Instar	0.49 ± 0.02 ^f	0.51 ± 0.10 ^f	0.32 ± 0.03 ^f	0.31 ± 0.09 ^f
3rd Instar	0.69 ± 0.02 ^e	0.73 ± 0.07 ^e	0.48 ± 0.02 ^e	0.48 ± 0.06 ^e
4th Instar	1.09 ± 0.07 ^d	1.05 ± 0.07 ^d	0.73 ± 0.06^a	0.69 ± 0.06^b
Female	2.10 ± 0.14 ^b	2.10 ± 0.26 ^b	0.65 ± 0.07 ^c	0.64 ± 0.05 ^c
Male	1.55 ± 0.09^c	2.7 ± 0.19^a	0.32 ± 0.04^f	0.61 ± 0.05^d
F (cal)	250.891		91.530	
CD	0.054		0.024	
SE(m)	0.020		0.008	
CV	10.453		11.089	

Note: N - 30; Numbers in bold are significantly different; F (cal) - calculated F-value; CD - critical difference; SE(m) - standard error of the mean; CV - coefficient of variation.

Elango and Nelson (2020) reported *E. guadeloupae* with body length and width of 0.675 ± 0.014 mm and 0.256 ± 0.010 mm, respectively. This particular size is correlated with the 3rd instar nymphal stage only. Moreover, later-stage nymphs were not preferred by *E. guadeloupae* (Saranya et al., 2021a) as their parasitisation may lead to the emergence of male parasitoids (Walter, 1983), which might be due to auto-parasitisation (Williams, 1996). The small size of males on coconut in comparison with oil palm is attributed to host nutritional support during developmental stages, as reported in *Trialeurodes ricini* (Huang et al., 2014; Shishehbor & Brennan, 1996). Above all, Logeshkumar et al. (2024) also reported morphometric variation in geographical isolates of RSW adults on coconut.

Survival analysis revealed that host plant effects on RSW were not significant (Table 2 and 3) during the early immature stages ($\chi^2_4 = 7.86$ – 3.81 , $p > 0.05$), indicating that 1st to 4th instar nymphs were able to survive across all tested hosts with relatively high probabilities (0.65–0.92). However, the effect of the host became highly significant during eclosion, i.e., from the fourth instar to the adult ($\chi^2_4 = 22.12$, $p < 0.001$). Adult emergence was greatest on custard apple (0.98 [0.86–0.99]) and ramphal (0.96 [0.86–0.99]), moderate on guava (0.87 [0.74–0.94]) and lowest on oil palm

(0.77 [0.60–0.88]) and coconut (0.71 [0.55–0.83]) (Table 2). Post hoc pairwise comparisons (Tukey correction) confirmed significantly higher adult survival on custard apple, ramphal and guava when compared with oil palm ($p < 0.05$). Random-effect variance due to colony identity was negligible ($\sigma^2 \approx 0$), suggesting that the observed differences were predominantly host-driven rather than colony-specific. A similar trend was also observed in the realised stage-specific mortality (Table 3) on the tested hosts, where eclosion (egg to 1st and 4th instar to adult) showed maximum mortality.

The consistent early-instar survival across hosts suggests that RSW nymphs can initiate feeding and maintain development on multiple host species. Yet, the marked decline in adult emergence on palms indicates physiological or nutritional incompatibilities. This pattern aligns closely with earlier findings by Stocks and Hodges (2012), who observed complete life-cycle development on custard apple and guava but incomplete pupation and adult formation. Similarly, Stocks and Hodges (2012) reported that although the species can colonise coconut, pupal mortality is high, leading to limited adult emergence. Saranya et al. (2021b) and Elango et al. (2019) also observed that RSW infestation is

TABLE 2. ESTIMATED MARGINAL MEANS (PREDICTED SURVIVAL PROBABILITIES $\pm$ 95% CI) OF RUGOSE SPIRALLING WHITEFLY (RSW) ACROSS DEVELOPMENTAL STAGES AND HOST PLANTS FROM BINOMIAL GLMMS

Host	1st instar	2nd instar	3rd instar	4th instar	Adult (4th $\rightarrow$ adult)
Oil palm	0.656 [0.55–0.75]	0.898 [0.79–0.95]	0.887 [0.77–0.95]	0.723 [0.58–0.83]	0.765 ^c [0.60–0.88]
Coconut	0.722 [0.62–0.81]	0.908 [0.81–0.96]	0.847 [0.73–0.92]	0.820 [0.69–0.90]	0.707 ^{bc} [0.55–0.83]
Guava	0.733 [0.63–0.81]	0.924 [0.83–0.97]	0.918 [0.82–0.97]	0.839 [0.72–0.91]	0.872 ^{ab} [0.74–0.94]
Custard apple	0.789 [0.69–0.86]	0.845 [0.74–0.91]	0.900 [0.80–0.95]	0.833 [0.71–0.91]	0.978 ^a [0.86–0.99]
Ramphal	0.822 [0.73–0.89]	0.892 [0.80–0.95]	0.909 [0.81–0.96]	0.867 [0.76–0.93]	0.962 ^a [0.86–0.99]
χ^2 (df = 4)	7.858	2.437	1.820	3.813	22.12
p value	0.097 ns	0.656 ns	0.769 ns	0.432 ns	< 0.001 ***

Note: Values represent estimated marginal means (predicted survival probabilities) on the response scale $\pm$ 95% confidence intervals. χ^2 and p values correspond to the likelihood-ratio tests for the host effect within each developmental stage (bottom two rows). Different letters indicate significant pairwise differences among hosts for the adult stage only (Tukey 's-adjusted $p < 0.05$). Asterisks denote significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns - not significant ($p > 0.05$).

TABLE 3. STAGE-SPECIFIC MORTALITY OF RUGOSE SPIRALLING WHITEFLY (RSW) ON DIFFERENT HOSTS

Stage	Stage-specific mortality (%)				
	Oil palm	Coconut	Custard apple	Ramphal	Guava
Egg to 1st instar	34.4	27.8	21.1	17.8	26.7
1st to 2nd instar	10.2	9.2	15.5	10.8	7.6
2nd to 3rd instar	11.3	15.3	10.0	9.1	8.2
3rd to 4th instar	27.7	18.0	16.7	13.3	16.1
4th instar to adult	23.5	29.3	2.2	3.8	12.8
Egg to adult	71.1	67.8	51.1	44.4	54.4

Note: A total of three colonies were observed for developmental stages of rugose spiralling whitefly (RSW) with each colony starting with 30 eggs.

sporadic and often fails to persist beyond a few generations. The congruence between laboratory survival data and field observations strengthens the argument that the oil palm is a sub-optimal or medium-preferred host.

The morphological developments in the nymphal stage of RSW on oil palm and their possible descriptions are presented in *Figure 1*. The total development period of RSW on oil palm (*Table 4*) from egg to adult was 38 ± 2.36 days, with maximum time in the egg stage (9.33 ± 0.82) and 4th instar (10.4 ± 0.51), followed by 1st instar (7.47 ± 0.52). Similar developmental periods were also noticed in coconut, viz., egg to adult of 36.53 ± 1.46 days, egg period of (8.13 ± 0.83) and 4th instar (10.67 ± 0.49), and 1st instar period of 6.07 ± 0.7 days. *T. ricini* also reported longer developmental times of egg and 4th instar compared to other developmental stages (Huang et al., 2014). On oil palm, RSW reported a total nymphal period of 28.67 ± 2.29 days and an egg-to-adult period of 38 ± 2.36 days. Saranya et al. (2021b) reported a slightly shorter developmental period from egg to adult in coconut (36.6 ± 0.71), banana (37.9 ± 0.67), sapota (36.6 ± 0.55) and similar in guava (38.6 ± 0.59). This slightly higher developmental period on oil palm may represent comparatively low preference, which also substantiates prior incidence of RSW on coconut rather than oil palm in every season, although coconut is grown as a border crop in oil palm gardens. The shortest life period of RSW, accounting for 31.1 days, was reported in white bird paradise (Boughton et al., 2015). In contrast, Pradhan et al. (2020) reported egg-to-adult periods of 27.4, 36.2, 31.9 and 32.9 days (calculated as per the table provided in the article) on coconut, banana, Indian shot (*Canna indica*), and banana under field conditions. These variations are probably due to variations in existing climatic conditions, either due to geographical variations or the time of study.

TABLE 4. DURATION OF LIFE STAGES OF RUGOSE SPIRALLING WHITEFLY (RSW) ON OIL PALM

Life stage	Duration (days)	
	Oil palm	Coconut
Egg	9.33 ± 0.82	8.13 ± 0.83
1st Instar	7.47 ± 0.52	6.07 ± 0.70
2nd Instar	5.07 ± 0.85	5.53 ± 0.52
3rd Instar	5.73 ± 1.39	6.13 ± 0.35
4th Instar	10.40 ± 0.51	10.67 ± 0.49
Adult	18.80 ± 1.42	20.27 ± 1.83
Total life cycle	56.73 ± 2.87	56.8 ± 2.46
Egg to adult	38.00 ± 2.36	36.53 ± 1.46
Total nymphal period	28.67 ± 2.29	28.4 ± 1.21

Note: N - 15 colonies with around 10 eggs left for development into adults. Values are mean $\pm$ SD.

Chronological progression of RSW development from nymph to adult stages: 1st Instar (D1 to D8), 2nd Instar (D9 to D13), 3rd Instar (D14 to D20), 4th Instar (D21 to D30), puparium exhibiting 'T' shaped exit hole (D31) and adult (D32) (*Figure 1*).

The favourable physical, physiological and biochemical features of the host portray the environmental fitness of pest feeding upon it, thereby influencing the shape and structure of the next trophic level, the natural enemies (Ode, 2006). In a polyphagous pest like RSW, the survival and development on a variety of hosts comes with a specific fitness cost (Jaenike, 1990). The data on the counts of developmental stages (nymphs and adults per colony) on five tested hosts (*Table 5*) revealed that ramphal is the most preferred host, evident by the lowest stage specific mortality (46.34% from egg to adult) with maximum number of surviving adults (15.2 ± 2.6) and nymphs (15.87 ± 2.9) per 30 eggs (*Table 5*). Therefore, ramphal can be considered the true host for RSW. The second-best group of hosts for the survival of RSW is custard apple and guava, followed by oil palm and coconut (*Table 5*). Interestingly, stage-specific mortality also showed clear variation among the hosts. Despite the maximum mortality from egg to 1st instar on all hosts, an overall mortality trend is decreasing in preferred hosts (guava, custard apple and ramphal) and increasing in less preferred hosts (oil palm and coconut). During eclosion, maximum mortality was observed in oil palm (23.5%) and coconut (29.3%), whereas it was least in custard apple (2.2%) and ramphal (3.8%) (*Table 3*). Taravati and Mannion (2014) also reported egg-to-adult survival of $28 \pm 4\%$, which is in agreement with the present study. Although reports identified significant variation amongst the hosts with respect to the number of eggs per colony (Taravati et al., 2018) no significant variation was observed amongst the selected hosts. Whereas, the nymphs and adults per colony showed host-specific survival. Amongst the hosts, maximum survival of nymphs was observed on avocado, guava, custard apple and ramphal. The maximum number of adults per colony was observed on ramphal, custard apple and guava. Oil palm and coconut showed a significantly similar number of adults per colony. But the number of nymphs per colony was significantly higher in coconut (*Table 5*). This might be due to the lowest mortality from nymphs to adults in oil palm (24.55%) rather than coconut (29.56%). Jackfruit and jamun are less suitable for sustaining RSW populations, as reflected by their high mortality rate during metamorphosis, which accounts for nearly 88.38% and 83.67%, respectively (*Table 5*). Overall, the low mortality rates on guava, ramphal and custard apple highlight their potential for fostering larger pest populations. The possible explanations with respect to host-

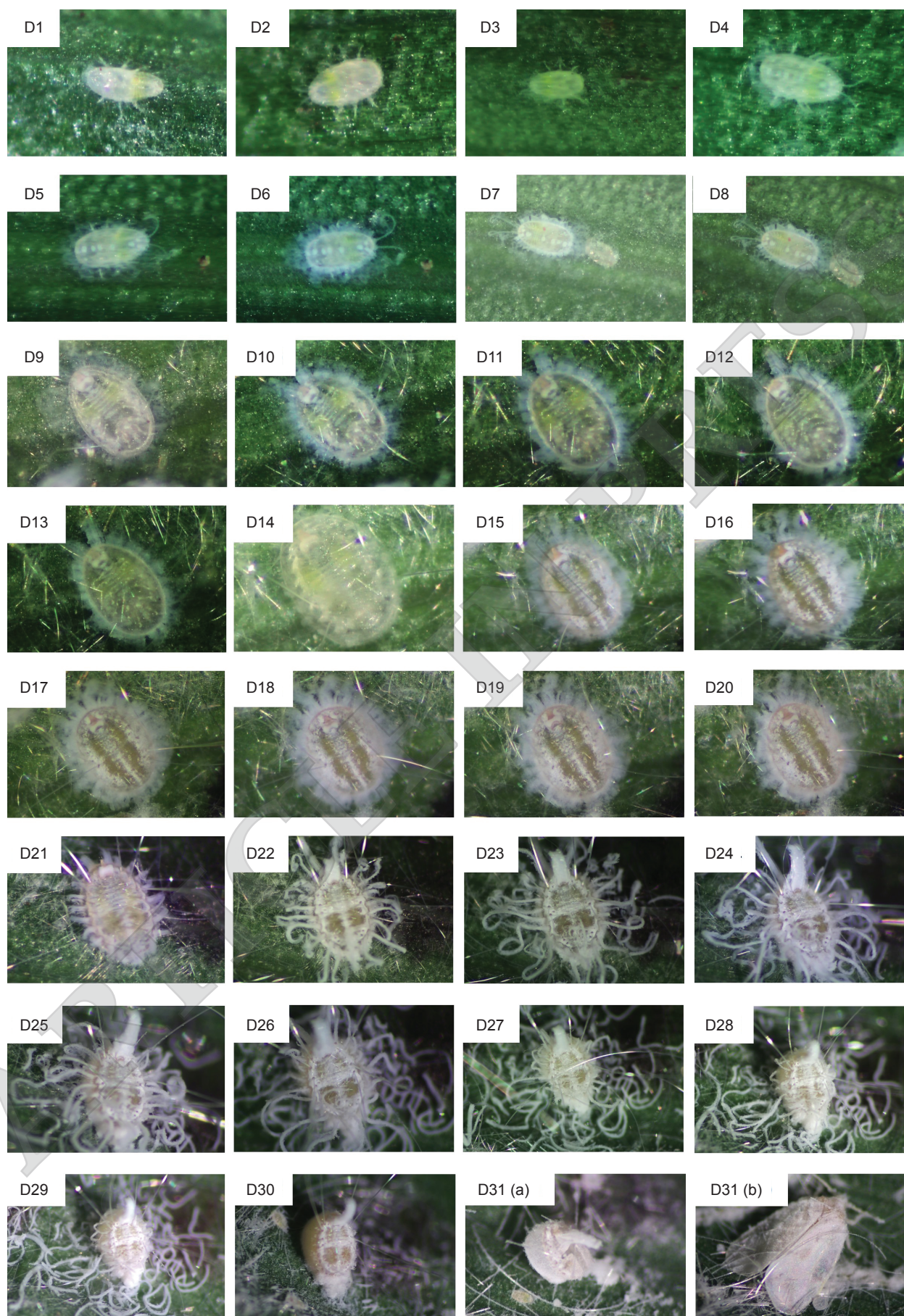


Figure 1. Morphological developments in the nymphal stage of rugose spiralling whitefly (RSW) on oil palm.

dependent arrangements of life stages with pictorial evidence are detailed in *Figure 2*. These hosts can be strategically leveraged for the conservation and augmentation of natural enemies.

The variability in colony morphology of RSW across the tested hosts was very meagre but statistically significant (*Table 5*). Amongst the hosts, oil palm recorded the maximum colony length (2.33 ± 0.07), followed by guava (2.01 ± 0.07) which were significantly different from the rest of the tested hosts. The width of the colony was significantly minimal in guava (1.08 ± 0.4). This may represent a possible alteration in egg-laying behaviour according to host leaf/leaflet structure or plant architecture (Taravati et al., 2018). A correlation study between the length and width of the colony and the number of eggs and nymphs per colony was done with oil

palm and coconut together (*Tables 6 and 7*). There was no significant difference in the number of eggs laid per colony between hosts which indicates RSW adults did not consider the host nutrient status for the progeny. Thus, the adults lay eggs on the base of the fronds, developing fruits and even on non-hosts like papaya, where no development of nymphs was observed. However, there is a significant difference in the number of nymphs per colony, which might be due to the host characteristics that support the development of the insect. Colony width, in instances such as eggs per colony in oil palm and nymphs per colony in coconut, has a significant correlation. Further sampling studies are required to identify the significant association. The morphometry of the 4th instar and adult male of RSW on different hosts exhibited some confusing values (*Table 8*) which may not be explained at this

TABLE 5. COMPARATIVE COLONY MORPHOLOGY AND POPULATION (EGGS, NYMPHS AND ADULTS) PER COLONY IN DIFFERENT HOSTS UNDER FIELD CONDITIONS

Host	Colony morphology (cm)		Life stages per colony			Percent mortality		
	Length	Width	Eggs	Nymphs	Adults	Egg to nymph	Nymph to adult	Egg to Adult
Oil palm	2.33 ± 0.07^a	1.52 ± 0.06^a	28.53 ± 4.3	11.13 ± 3.1^c	8.4 ± 2.6^c	60.98	24.55	70.56
Coconut	1.72 ± 0.07^c	1.28 ± 0.07^b	30.07 ± 10.2	13.53 ± 2.0^b	9.53 ± 2.3^c	54.99	29.56	68.29
Guava	2.01 ± 0.07^b	1.08 ± 0.4^c	31.8 ± 5.1	16.53 ± 3.6^a	14.4 ± 4.4^{ab}	48.01	12.90	54.72
Custard apple	1.72 ± 0.06^c	1.40 ± 0.05^{ab}	30.4 ± 4.4	14.8 ± 3.9^{ab}	14.73 ± 2.9^{ab}	51.54	0.45	51.32
Ramphal	1.71 ± 0.09^c	1.47 ± 0.05^a	28.33 ± 4.4	15.87 ± 2.9^{ab}	15.2 ± 2.6^a	46.35	4.39	46.34
Pomelo	1.71 ± 0.08^c	1.39 ± 0.05^{ab}	29.87 ± 3.2	15.93 ± 2.2^a	13.4 ± 2.5^b	46.65	15.90	55.13
Jackfruit	1.65 ± 0.06^c	1.45 ± 0.07^a	30.13 ± 4.6	6.13 ± 2.4^d	3.53 ± 1.2^d	80.09	41.67	88.38
Jamun	1.65 ± 0.06^c	1.40 ± 0.07^{ab}	30.2 ± 3.5	7.2 ± 2.5^d	4.93 ± 2.3^d	76.16	36.51	83.67
F (cal)	8.18	4.45	NS	31.752	47.9			
CD (0.05)	0.213	0.17		1.99	1.912			

Note: N - 30 colonies per life stage in each host are studied; F (cal) - calculated F-value; CD (0.05) - critical difference at the 5% significance level.

TABLE 6. COLONY MORPHOMETRY WITH LIFE STAGES OF RUGOSE SPIRALLING WHITEFLY (RSW)

Colony morphometry and life stages	Coconut	Oil palm
Colony length	1.99 ± 0.31	1.98 ± 0.56
Colony width	1.51 ± 0.32	1.39 ± 0.33
Number of eggs per colony	31.5 ± 14.18	25.11 ± 13.12
Number of nymphs per colony	28 ± 8.41	15.88 ± 10.36

TABLE 7. CORRELATION BETWEEN COLONY PARAMETERS AND NUMBER OF LIFE STAGES

Life stage and host	Colony morphology	Correlation	Significant at 5%
Eggs per colony in oil palm	Colony length	0.421	NS
	Colony width	0.546	S
Nymphs per colony in oil palm	Colony length	0.339	NS
	Colony width	0.381	NS
Eggs per colony in Coconut	Colony length	0.121	NS
	Colony width	-0.038	NS
Nymphs per colony in Coconut	Colony length	0.260	NS
	Colony width	0.556	S
Eggs + nymphs per colony in both hosts	Colony length	0.304	S
	Colony width	0.295	S

Note: Correlation is significant at the 0.05 level. N - 30; NS - not significant; S - significant.

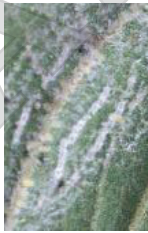
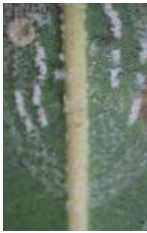
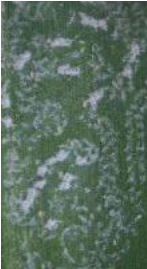
Host	Egg laying patterns	Nymphal feeding pattern	Adult arrangement	Probable reasons for nymphal proliferation in different hosts
Guava				• Arrangement of nymphs fairly perpendicular to the feeding site/ veins and veinlets. • Easiness to find the feeding site. • Nymphs here have better protection against harsh winds and rainfall, as they are sheltered by the grooves and ridges of leaf veins. • Abaxial leaf surface is not glossy and tough and easy to penetrate.
Custard apple				
Ramphal				
Jamun				• The texture of the leaf is smooth and a little glossy, which affects the movement of the 1st instar, thus making it difficult to find a suitable feeding spot. • Relatively thick leaves, which may not allow or provide a proper feeding site. Resulting in mortality of early instars. • Although they exhibit reticulated venation, their grooves and vein ridges are less pronounced compared to those found in guava, custard apple and ramphal. Additionally, their glossy or waxy surface further hinders the development of nymphs.
Jackfruit				
Oil palm				• Lack of raised veins and smooth surface; may not provide the security to nymphs against winds and rainfall in comparison to guava, ramphal and custard apple. • Initial nymphal arrangement is parallel to veins and veinlets but does not settle in the same fashion.
Coconut				

Figure 2. Host-dependent arrangement of rugose spiralling whitefly (RSW) life stages and their possible explanations in development.

TABLE 8. MORPHOMETRY OF 4TH INSTAR AND MALES OF RUGOSE SPIRALLING WHITEFLY (RSW) ON DIFFERENT HOSTS

Host	4th Instar		Adult male	
	Length	Width	Length	Width
Oil Palm	1.02 ± 0.06 ^{cd}	0.68 ± 0.05 ^b	2.69 ± 0.19 ^b	0.61 ± 0.04 ^b
Coconut	1.1 ± 0.05 ^{ab}	0.73 ± 0.05 ^a	1.54 ± 0.07 ^c	0.32 ± 0.03 ^c
Custard apple	1.06 ± 0.05 ^{bc}	0.75 ± 0.05 ^a	2.95 ± 0.31 ^a	0.61 ± 0.04 ^b
Ramphal	1.01 ± 0.06 ^d	0.68 ± 0.07 ^b	2.78 ± 0.3 ^{ab}	0.62 ± 0.06 ^b
Guava	1.11 ± 0.06 ^a	0.76 ± 0.05 ^a	2.99 ± 0.26 ^a	0.66 ± 0.02 ^a
F (cal)	8.78	6.25	52.41	106.96
CV	5.42	8.05	10.1	7.47
CD (0.01)	0.056	0.057	0.318	0.051

Note: F (cal) - calculated F-value; CV - coefficient of variation; CD (0.01) - critical difference at the 1% significance level.

point. Moreover, the adult males are very sparsely visible on coconut, oil palm, guava, custard apple and ramphal. This phenomenon is supported by the study on *T. ricini* (Shishhebor & Brennan, 1996) and *Bemesia tabaci* (Bethke et al., 1991), where the development of more females was observed on the most suitable host plants.

As a whole, the above results suggest some favourable and unfavourable hosts in comparison to oil palm as a host for RSW. Utilisation of this data in ecological engineering through a plant-based augmentation of biological control agents in oil palm results in minimal interventions in the sustainable management of RSW. Saranya et al. (2021a) demonstrated that *Encarsia guadeloupae*, a potential parasitoid against RSW, efficiently parasitises the nymphs on guava. Aligning with these findings, our study identified guava, custard apple and ramphal as promising host plants that support substantial nymphal populations. So, there is a possibility of using them as reservoirs for the conservation of natural enemies like *E. guadeloupae* in any given plantation of oil palm. Similarly, *Pseudomallada astur*, a potential green lacewing predator of RSW, can also be conserved on these hosts, which may support a continuous supply of prey. A specific behaviour of adults of RSW, i.e., returning to the colony (nesting fidelity) after egg laying in new areas (Taravati et al., 2018), may also be explored for the spreading of conidia of microbial biocontrol agents like *Isaria fumosorosea* pfu5 and R55 through the auto-dissemination technique (Vickers et al., 2004) by targeted spraying towards the strategically located preferred hosts in the oil palm plantation. Such ecological engineering by using these highly preferred hosts can be hypothesised as “banker crops” in an oil palm plantation, which may support sustainable and natural pest management. However, extensive studies are warranted about the strategic location (either within the garden or on field edges) of banker hosts and their ratio per unit land of the oil palm plantation.

The seasonal incidence of RSW only during non-rainy periods and high incidence of pests, especially on border palms, also supports the concept of trap crops and barrier crops. Border plantation of these pest-supportive host plants (guava, custard apple and ramphal) attracts the spreading population of RSW, which may delay the incidence on the main crop (oil palm). Conversely, unpreferred or less preferred hosts like jackfruit and jamun can be considered as barrier crops which restrict the spread within the plantation through unfavourable host interactions.

CONCLUSION

Integrating host plants with varying susceptibilities to RSW into pest management strategies optimises natural enemy roles and enhances biological control. In the present study, the survival and developmental biology of RSW on oil palm in both laboratory and field conditions revealed that oil palm is a medium-preferred host with the lowest survival periods and population buildups. Similarly, hosts like ramphal and custard apple supported high population buildup. These high-performing hosts can support biocontrol augmentation and dissemination for sustainable pest management, thereby enhancing agricultural resilience to RSW outbreaks. However, RSW can remain a potential key pest of oil palm in view of the existing vast area coverage. Keeping in view the perennial nature of oil palm, adopting the concept of ecological engineering may yield sustainable pest management for regional agroecosystems.

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