Mui-Yun Wong *Editor*

Advances in Tropical Crop Protection

Springer

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ISBN 978-3-031-59267-6 ISBN 978-3-031-59268-3 (eBook)
https://doi.org/10.1007/978-3-031-59268-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The United Nations (UN) has proclaimed the year 2020 as the International Year of Plant Health with a slogan “Protecting Plants, Protecting Life”. This shows the utmost importance of healthy plants to humans and planet Earth. This proclamation is expected to increase awareness about the importance of healthy plants in achieving the Sustainable Development Goals (SDGs) where they have a direct impact on five SDGs: SDG1 end hunger, SDG2 reduce poverty, SDG8 boost economic development, SDG13 mitigate climate change, and SDG15 protect the environment. Besides, healthy plants ensure food security for the growing global populations which is expected to reach 9 billion in 2050.

Modern crop production systems utilize intensification model involving intensive use of farm input such as water, fertilizers, and pesticides. A major component of crop production is pest and disease management. FAO estimates that up to 40% of food crops are lost due to plant pests and diseases annually. To reduce yield losses caused by pests and diseases, synthetic pesticides are commonly used, often injudiciously, due to their immediate and indiscriminate effects, relatively low cost, and easy availability in the market. Global use of pesticide went up 62% between 2000 and 2021 (FAO, 2023). Extensive use of synthetic pesticides causes hazard on living organisms as well as pollution to underground water, degradation of good soil, reduction in biodiversity, and pest resistance—issues of grave concern among many stakeholders.

While pesticide use is necessary to increase yield to feed a growing population, it is considered the last option in the integrated pest management approach. Non-chemical strategies for crop protection that are safe for living organisms and the environment are available. Conservation of natural enemies and high species diversity in the agroecosystems often reduce the risk of pests and diseases in general. This book entitled *Advances in Tropical Crop Protection* focuses on innovative nature-based solutions for sustainable crop protection in plantation and food crops.

There are 16 chapters in this book and organized into three parts. First part describes research advances related to tropical insect pest management including bagworm and red palm weevil bio-based management; sustainable management of thrips infesting vegetables; biology and potential application of baculoviruses as biopesticides; nature-based substances for enhanced biopesticide efficacy against insect pests; as well as biology and integrated pest management (IPM) of pink pineapple mealybug. Second part covers advances in plant disease management in the tropics including description of a newly emerging rubber disease; descriptions of common diseases in pineapple and their management; microbiome of banana and its manipulation for management of Fusarium wilt disease; utilization of plant-based product in post-harvest disease management of fruits; updates on infection and control strategies of basal stem rot disease of oil palm in Malaysia; revolution of the next-generation sequencing and its application in phytobacterial diseases; and lastly utilization of plant and microbial diversity in disease management. Third part embarks on research advances related to management of other tropical pests including vertebrate pest management; sustainable rat management model in rice field; threats and management of invasive apple snails; and development of bioherbicides for sustainable weed management.

With stand-alone chapters written in an accessible language, the book is recommended for research scientists in academia and industry, readers particularly interested in crop protection, and those working within the broader area of plant biosecurity.

To keep plants healthy and feed the increasing world population, nature-based crop protection for sustainable agriculture is the way forward. The solutions that nature has developed provide us the inspiration for further innovations in crop protection.

Serdang, Malaysia Mui-Yun Wong

Acknowledgements

The editor would like to sincerely thank all contributing authors for accepting this invitation and making this book a reality. Their continuous cooperation and commitment in this project are much appreciated. I am also thankful to Associate Professor Dr. Norida Mazlan, the Head of Department of Plant Protection, Faculty of Agriculture, Universiti Putra Malaysia, for her support in the publication of this book. Furthermore, I am extremely grateful to Dr. Go Wen Ze for her professional and technical assistance in the process of preparing the book manuscript. Last but not least, I appreciate the opportunity given by Springer Publisher and its team for their support and valuable advice in the production of this book.

Contents

Advances in Tropical Insect Pest Management

Bagworm and Red Palm Weevil—Major Pest and Potential Threat to the Malaysian Oil Palm Industry

Muhamad Haziq Hadif Zulkefli, Syari Jamian, Nur Azura Adam, Sumaiyah Abdullah, Siti Izera Ismail, and Mohamed Mazmira Mohd Masri

Abstract *Elaeis gunineensis* is the golden crop of Malaysia that contributes to the economic export of the country and the planters' livelihood. Despite control measures to overcome the issue, bagworm remains the most reported infesting oil palm cultivation in the last four decades. Furthermore, the coconut areas in oil palm plantations documented an invasive alien species infestation, the *Rhynchophorus ferrugineus* or red palm weevil (RPW). The widespread devastation the pests caused on palm cultivation worldwide has served as warning to the industry, primarily in Malaysia, where palm oil is the main commodity. The present study highlights the current report on the biology, control, and technological advancements in bagworm management. A recent report on the RPW concerning its biology, detection, the scenario in oil palm plantations, and control methods investigated in past studies was also discussed. This study could offer new insights on the pest and its potential threats to oil palm cultivation in Malaysia.

Keywords Oil palm · Bagworm · Red palm weevil

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M. Wong (ed.), *Advances in Tropical Crop Protection*,
https://doi.org/10.1007/978-3-031-59268-3_1

1 Introduction

Oil palm is a crucial commodity in Southeast Asian countries, especially Malaysia and Indonesia. In 2021, the Malaysian Palm Oil Board (MPOB) estimated the area of palm oil cultivation in Malaysia at approximately 5.8 million hectares (ha) (MPOB, 2021), comprising almost 90% mature, while the remaining percentage was immature palms. The cultivated land was segregated between plantations, around 70%, and smallholders (MPOB, 2021).

Parveez et al. (2021) discovered that reduced cultivation area, low fresh fruit bunch (FFB) yield, and decreased palm oil and palm oil-based product export in 2020 did not impact palm oil export value. Conversely, an approximate increase of 9% (RM 73.25 million) was documented compared to the past year. In 2020, palm oil products were the fourth largest export, accounting for 4.7% of Malaysian exports (Malaysia External Trade Development Corporation, 2021).

In oil palm cultivation, pests threaten the potential FFB yield. Bagworm is the most significant pest plaguing the industry (Moslim et al., 2019). The pest feeds on defoliating fronds. In severe cases, the fronds appear burned. At a 10–50% infestation rate, the insect has impacted oil palm yield by 43% (Basri & Kevan, 1995).

Bagworms were first documented in the late 1950s. The pest is commonly found in Peninsular Malaysia (Wood & Kamarudin, 2019) in three species: *Metisa plana* (*M. plana*), *Pteroma pendula* (*P. pendula*), and *Mahasena corbetti* (*M. corbetti*) (Mazmira et al., 2011; Moslim et al., 2019). Bagworm management is crucial to ensure healthy and productive oil palms as the life span of the plants could exceed 25 years. Meanwhile, the potential threat of *Rhynchophorus ferrugineus* or the red palm weevil (RPW) has become a new concern in the Malaysian oil palm industry besides bagworm. The pest has been reported to be plaguing coconuts, a subsidiary commodity industry of the country. Globally, RPW has also been established as a significant pest of the palm species (Dembilio & Jaques, 2015). In 2007, the Malaysian Department of Agriculture (DOA) reported RPW issues in all coconut plantations in Terengganu, Malaysia (Wahizatul et al., 2013b). The symptoms of a severe RPW attack are collapsed crowns and instant death of coconut palms (Wahizatul et al., 2013b). As coconut shares the similar Aceraceae family as oil palm (Perera, 2014), RPW threatens the Malaysian oil palm industry, which could devastate the golden crop and planters' livelihood.

This study summarises current reports on bagworm infestation and management methods and discussed integrated pest management (IPM) for bagworms in the field. Moreover, findings on coconut infestation and oil palm plantation surveillance at Malaysian climates were included. Moreover, the study provides a brief review of the current scenario on the pests and possible management approaches to control the pests.

2 The Primary Malaysian Oil Palm Pest

2.1 Occurrence, Lifecycle, and Damage Caused by Bagworms in the Malaysian Climate

Bagworm is the major pest attacking the oil palm industry in Malaysia, which could result in devastating impacts due to ineffective management. *M. plana* Walker, *P. pendula* Joannis, and *M. corbetti* Tams (Lepidoptera: Psychidae) are the three common bagworm species documented in the country. Wood and Kamarudin (2019) reported that the bagworm outbreak in Malaysia began in late 1950 but remained under control from the mid-1960s to 1990.

A survey between 2000 and 2005 recorded 16% of the surveyed area, reported bagworm outbreaks, mainly by *M. plana* and *P. pendula* and a few with *M. corbetti* (Norman & Basri, 2007). Additionally, Moslim et al. (2019) documented a significant bagworm attack in 2013 in the Perak and Johor states of Peninsular Malaysia, while a smallholder reported that 24, 385.9 ha was infested with bagworm in 2014s (Kamarudin et al., 2015).

The life cycle of a bagworm varies according to species. Currently, the bagworm of the *M. plana* species is the most widely reported and documented with the most complete life cycle (see Fig. 1.1) (Basri & Kevan, 1995; Kok et al., 2011). The life cycle of bagworms from egg to adult is 90–103 days. Nonetheless, *P. pendula* could live almost three months (Radaha, 1977; Syed, 1978), while *M. corbetti* has been recorded with a 101–124 day life cycle (unpublished MPOB data; Ramlah et al., 2018).

Wood and Kamarudin (2019) suggested that systemic pesticide applications led to infestation surges considering its impact on the biological control of the pest. Accordingly, the bagworm life cycle has been utilised in the field as an indication for pesticide applications. Pesticides commonly focus on the eating behaviours of larvae as the chemicals could not penetrate bagworm bagging. Consequently, bagworm management is recommended during the early larvae stages when its population exceeds the economic threshold level (ETL) (Moslim et al., 2019) of 5–10 larvae per frond for *M. plana* and *P. pendula* and 1–5 larvae per frond for *M. corbetti* (Chung, 1998; Chung et al., 1995; Syed & Speldewinde, 1974).

Matured palms of over eight years are susceptible to bagworm defoliations (Ramlah et al., 2018). Young bagworm larvae scrape the epidermis layers of the oil palms, whereas the older larvae strip the epidermis and create holes in the oil palm leaflets (Moslim et al., 2019; Ramlah et al., 2018). The symptoms of bagworm damage initiate on the older fronds and continue to the younger fronds (Moslim et al., 2019). Severe damage is indicated by burn-like or brownish areas (Moslim et al., 2019).

Wood et al. (1973) reported that 50% defoliated fronds results in 43% yield loss. In another study, Basri (1993) revealed 44% of yield loss from 10 to 13% leaflet bagworm defoliation. Both studies demonstrated that bagworm defoliation under 20% could impact FFB production to almost 50%, indicating significant effects by

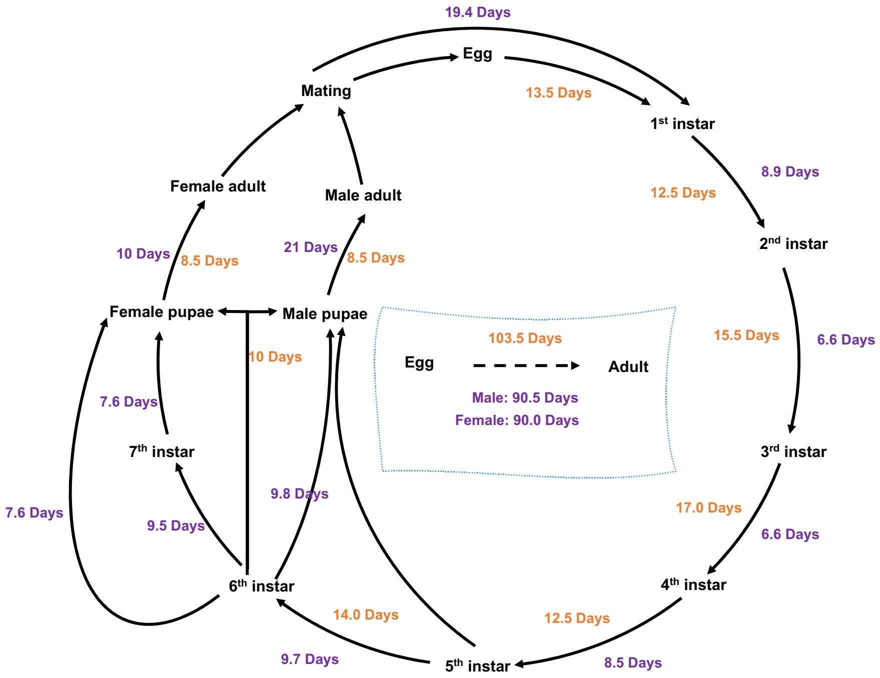

Fig. 1.1 Complete life cycle of *Metisa plana* summary indicated by day for each stage. *Note* The colour of the day denotes reference citation; purple: Basri and Kevan (1995) and orange: Kok et al. (2011)

the pest could have on oil palm cultivation, primarily when not maintained below the ETL. Nonetheless, notable and recent advancements have been reported on bagworm management through integrated pest management (IPM).

2.2 Latest Technology Advancements and Research on Bagworms in Malaysia

Artificial intelligence for bagworm census tool is available and among them is the Oto-BaC™ an advanced artificial intelligence (AI) detector manufactured to detect live and dead bagworm larvae of the *M. plana* species during field censuses compared to the manual censuses conducted at the moment (Ahmad et al., 2021). The data evaluated during trials indicated that the detector could detect live bagworm larvae and pupae at 77–88% accuracy, while 75–79% accuracy was recorded for dead larvae and pupae. Conversely, manual census documented 100% accuracy.

The Oto-BaC™ detector documented a shorter census period per frond, approximately 14 min/frond, compared to the manual census, which recorded approximately

17 min/frond (Ahmad et al., 2021). In a similar study by Ahmad et al. (2021), a 30 cm distance and a closed system enabled 100% detection of bagworms with the deep learning algorithm, while the colour processing documented under 60% of detection.

Several factors still require consideration to improve the accuracy of the detector. Ahmad et al. (2021) stated that low detection resulted from bagworm sample size, light, field surface area, and the technology of the detector. Nevertheless, the detector has initiated advancements in bagworm detection in Malaysia, which could aid field censuses.

Live pheromone trapping has been employed to manage adult moths. Several studies utilised live female adult *M. plana* bagworms in pheromone trapping to manage bagworm regeneration in oil palm cultivations (Ahmad et al., 2017; Kamarudin & Arshad, 2006; Kamarudin et al., 2010). Kamarudin and Arshad (2006) employed three trapping models to evaluate the most suitable approach for trapping *M. plana* bagworms. Therefore, the vane trap employing four female bagworm adults as pheromone sources was the best design that captured the highest number of adult male catches per trap. Furthermore, the model reduced subsequent generation population and offspring.

Kamarudin et al. (2010) revealed no significant difference in the number of moths trapped when sticky vane traps on 2- and 4-m wooden poles were employed in areas with taller oil palms. Nevertheless, the report documented diminished second-generation larvae, fewer baggings with eggs, and fewer larvae per frond. The study also recorded minimal frond damage and heavier bunches of the trapping areas (Kamarudin et al., 2010).

Pheromone trapping has been proven effective in reducing bagworm populations to manageable levels. Nevertheless, the approach necessitates correct and timely assessments of female adult receptivity and a prior stage census of the infestation in the treated areas to prevent recurrent larvae in the next generation (Ahmad et al., 2017). According to Kamarudin and Arshad (2006), female *M. plana* adults are receptive to mating for nine days. Consequently, perfect timing is critical to ensure more populations are suppressed from being mated by the male moths to achieve new generation reduction. In another accordance, the incorporation of *Bacillus thuringiensis* (Bt), aerial spraying into pheromone trapping areas resulted in a 94% decrement in the bagworm population, which was higher compared to non-incorporated sections (Ahmad et al., 2017).

Biopesticides offer potential applications in oil palm plantations to manage bagworm populations and reduce the synthetic pesticide impacts on beneficial insects. For example, cypermethrin application has reportedly led to high mortality in pollinating weevil *Elaeidobius kamerunicus* (Najib et al., 2009, 2012; Norhayu & Nurnisa, 2020; Yusdayati & Hamid, 2015).

Three consecutive treatment cycles with Bt or Ecobag-1 (EC) through aerial spray significantly reduced bagworm larvae per frond of the oil palms cultivated in Perak (Kamarudin et al., 2017). The first, second, and third applications diminished the larvae population by 89.9, 92.9, and 88.2%. Moreover, the final assessment on the third cycle of the larvae per frond was, on average, 6.1 lower than the proposed ETL of 10 larvae per frond. Damaged (burned or brownish appearance) oil palm fronds also exhibited improved health (green) after two years of Bt application.

Masri et al. (2021) applied EC via drones to manage bagworms in multiple stages. Two treatment rounds of the biopesticide suppressed the larvae population to 9.3 larvae per frond. Furthermore, no pupae were documented on the final assessment post the second-round application. The first treatment cycle considerably reduced the number of larvae by 96%, while 91.5% was documented in the second-round application. Significant differences were also observed between the control plot, which did not receive the Bt treatment, and the treated areas after two years. The palms sprayed with EC demonstrated improved conditions, from a burned-like appearance to lush green (Masri et al., 2021).

Mazuan et al. (2021) employed different pesticides with mist blowers to control bagworm populations. The report recorded absence of notable variations between the EC and synthetic pesticides, flubendiamide, and cypermethrin, employed. All pesticides in the report recorded the ability to suppress the *M. plana* population up to 45 days post-application. The study revealed the potential of biopesticide to control pest populations to manageable levels below ETL in oil palm plantations.

Predators and parasitoids are natural organisms employed in oil palm cultivations to manage pest populations. According to Cheong et al. (2010), bagworm mortalities associated with predators, parasitoids, and fungal infections were 37%, 35.9%, and 27.2%, respectively. *Colmelestes picticeps, Callimerus arcufer* (Cheong et al., 2010), and *Sycanus dichotomus* (Ramlah et al., 2018) are some examples of bagworm predators. *Colmelestes picticeps* resulted in 60–100% bagworm mortality, while *C. arcufer* led to 23–40% of deaths. Nevertheless, the mortality rates of both predators differed based on the bagworm type (Cheong et al., 2010). Furthermore, a higher number of *C. picticeps* than *S. dichotomus* was reported during bagworm outbreaks (Jamian et al., 2017).

Based on a taxonomy report, 18 parasitoid species are correlated to bagworms (Kamarudin et al., 1996). According to Cheong et al. (2010), the primary parasitoids identified affecting bagworms were *Pediobius imbrues*, *Dolichogenidae matesae*, *P. elasmi*, and *Aulosaphes psychidivorus*, which respectively documented approximately 70, 10, 9, and under 8.5% parasitising the bagworm samples assessed. In another study, the largest number of parasitoids emerging from bagworms were *Cotesia metesae* (51%), *Brachymeria carinata* (21%), *Buysmania oxymora* (13%), and *Goryphus bunoh*, *Pediobius* sp., and *Eupelmus cotoxanthae* (under 9%) (Halim et al., 2017).

Jamian et al. (2017) reported that the abundance of *S. dichotomus* and *C. picticeps* predators increased with enhanced beneficial plant richness and ground vegetation coverage and shorter oil palm stands. Beneficial plants and weeds are crucial for parasitoid and predator sustainability and in one study by Kamarudin and Wahid (2010) documented that parasitoids *Cassia cobanensis* and *Asystasia gangetica* preferred areas with beneficial plants and weeds over grounds covered with other plants, such as weeds and ferns. The beneficial plant *C. cobanensis* exhibited a higher insect predator and parasitoid diversity than covered ground sections in oil palm plantations (Kamarudin & Arshad, 2016).

The lower number of parasitoids in covered grounds was believed to be due to the scarcity and unavailability of food sources. *C. picticeps* and *C. arcufer* documented in the area compared to absolutely no *S. dichotomus* captured on the grounds indicated the dependency of *S. dichotomus* on beneficial plants (Kamarudin & Arshad, 2016). Beneficial plants are one of the natural supports of predator and parasitoid populations in oil palm cultivated areas.

3 Potential Threats to the Malaysian Oil Palm Industry

3.1 The RPW Biology, History, and Scenario in Malaysia

The RPW, or *Rhynchophorus ferruginius* Olivier (Coleoptera: Curculionidae), is a potential threat to Malaysian oil palm cultivation. The pest was reported as the world's most destructive pest (Abbas, 2010), with numerous reports of infestations in the palmae family. In Malaysia, RPW was detected in *Cocos nucifera*, a coconut species cultivated in the country (Azmi et al., 2017; Wahizatul et al., 2013b).

The DOA reported the first RPW report in Malaysia was in 2007, infesting coconut plantations in Terengganu (Wahizatul et al., 2013b). The severity of the spread and damage was documented in 58 locations within seven Terengganu districts, including areas approaching the borders of Kelantan and Pahang. Nevertheless, the infestation increased to 858 locations in 2011 (DOA, 2011), and by 2016, it had spread to Kedah, Kelantan, Terengganu, Perlis, and Pulau Pinang (DOA, 2016). The observations proved the rapidness of RPW infestation (DOA, 2016).

Wahizatul et al., (2013b) hypothesised that RPW was introduced to Malaysia through dates and date palm tree importation from the Middle East. The pest was reported to attack four common coconut cultivars in Malaysia: MATAG, Malayan tall, MAWA, and Pandan (Wahizatul et al., 2013b). The shoots, trunks, and root systems of coconut trees were reported as RPW entry points (Wahizatul et al., 2013b). The RPW attacks straight to the cabbage of coconut palm shoots and drill or utilises holes made by *Oryctes rhinoceros* beetles on the trunks. Adult RPW also digs the soil around the coconut roots before tunnelling into the root systems (Wahizatul et al., 2013b).

Severe RPW damage could lead to crowns falling and instant death to coconut palms (Wahizatul et al., 2013b), thus demonstrating its grave threat to palm cultivation. In oil palm plantations, several studies conducted censuses to determine the presence of the pest. Samplings conducted via trapping in several oil palm cultivation areas, including FELDA, FELCRA, and TDM, documented 40% of RPW among the weevil accumulated (Idris et al., 2014). The study also recorded RPW at the centre of the plot. Although no damage symptoms were documented, the pest still concerns the oil palm industry as it is the primary source of income for the planters in Malaysia. Consequently, utilising advanced sensing technologies, such as acoustic detection (Khudri et al., 2021), requires consideration to confirm the presence of feeding larvae.

3.2 The RPW—A Potential Threat to Oil Palm

Studies have conducted through censuses in oil palm plantations in order to observe the presence and population of RPW. The surveys employed baiting with RPWlure and Ferrolure and acoustic detection monitoring devices. Based on the baiting approach, 40% of the RPW captured in several oil palm cultivation locations (FELDA, FELCRA, and TDM) was of the *R. ferrugenius* species (Idris et al., 2014). Moreover, the pest was documented at the centre of the plots. However, no damage symptoms on the oil palm were observed (Idris et al., 2014).

In another study, DOA collected the larvae, pupa, and adult RPW from the apical shoots of two dying oil palm trees at a smallholder's plantation in Tanah Merah, Kelantan (Khudri et al., 2021). The MPOB randomly installed IoTree smart sensors on 38 trees in the study site. Five suspension noise movements were recorded in the palms after a month of installation, and on the second month of observation only one tree remained infested. A further acoustic detection with an AED 2010 sensor implanted on the stem of the infested palm yielded a negative for RPW. Further inspection recorded three male RPW were found on the frond of a suspected infested palm post chopping of the palm. The findings demonstrated the effectiveness of the IoTree sensor in detecting RPW movement. Based on the results, acoustic detection possessed promising results for early RPW detections. Nonetheless, RPW could still bore the tree without being detected by the sensor. The findings demonstrated the possibility of RPW presence in oil palm trees without resulting in significant observable damages. Consequently, regular monitoring is necessary to ensure that the weevil does not shift host, which could damage the plantation.

A food consumption study by Zulkifli et al. (2018) documented that coconut and oil palm cabbages and sago stems were the preferred nourishment for RPW. Nevertheless, when comparing development periods, oil palm cabbages induced a faster growth at one month and nine days and only six instar stages before the RPW larvae entered the pupal stage. Meanwhile, RPW larvae that consumed coconut cabbages required almost three months, while sago stems recorded almost four months of growth. The RPW larvae that fed on both food sources recorded seven instar stages before pupation (Zulkifli et al., 2018). The data demonstrated that RPW larvae required double the time to develop when consuming coconut cabbages and sago stems than oil palm cabbages. The study also documented a critical finding that associated proteins with RPW larvae RPW diet; the trypsin (cationic trypsin) and aminopeptidase enzymes. It was also noted that protein is essential for the digestive and defence systems of the insect. Accordingly, trypsin and aminopeptidase could be utilised to create biological control agents for RPW and disrupt its feeding behaviour. The report revealed the possibility of RPW larvae surviving and developing faster on oil palm cabbages. Consequently, successful RPW infestation could significantly damage oil palm plantations.

Harith-Fadzilah et al. (2020) artificially infected oil palm seedlings with RPW larvae in an investigation. The larvae required approximately nine weeks to impose serious damage to two-year-old oil palm seedlings, which caused the fronds to collapse. The study divided the level of damage into four stages. The first stage included no visual damage, while the seedlings classified in the second stage exhibited smelly saps, dark ooze, and the presence of sawdust on their trunks. The third stage included seedlings with signs of frond collapse. In the final stage, the trees collapsed and demonstrated brown colouration on their fronds. Despite the severe damage the larvae could impose on seedlings, an in-depth study is still necessary to assess its impact on matured palms.

Photosynthesis rate could be another damage severity indicator of RPW-infested palms, but to set it as a standard, thorough investigations are still required (Harith-Fadzilah et al., 2020). Harith-Fadzilah et al. (2020) suggested that RPW larvae feeding on oil palm seedlings reduced the photosynthesis rate of the plants in the third week of infestation, during which no signs of damage were observed. Nevertheless, the seedlings sustained severe damage by the end of the study. No significant variation in the total chlorophyll, stomatal conductance, and seedling growth was reported between the wounded and control palms. The report suggested a more immediate impact that RPW larvae had on younger oil palm seedlings without visible damage until the infestation reached the severe stage.

The effect of invasive alien species (IAS) on the native plant population could lead to local extinction through reduced host plant population and plant death (Kenis et al., 2009; Pyšek et al., 2020). This phenomenon could indirectly affect local plant communities (Kenis et al., 2009). Invasive insects reportedly displace local insect populations. For example, another *Bemisia tabaci* biotype had displaced the local species by interfering with the mating of the local species (Kenis et al., 2009). Similarly, RPW resulted in the faster spread of IAS within local coconut palm hosts in Malaysia, which was documented in several districts in the country (DOA, 2011, 2016). The IAS has determinant effects on locally cultivated plants and insect populations competing in the same niche. Consequently, monitoring and preventing RPW spread is crucial to curbing invasive organisms.

3.3 Other Studies Related to RPW in Malaysia

Identification is vital to differentiate between the *Rhynchophorus vulneratus* and *R. ferrugineus* species. *R. vulneratus* is native to Malaysia and is a pest of coconut and sago palms. On the other hand, *R. ferrugineus*, or RPW, is an organism of concern. Wahizatul et al., (2013b) documented over 30 size, colour, and pronotal marking variations of adult RPW that attacked coconut plantations in Terengganu, Malaysia. Nevertheless, early morphological evaluations could not distinguish the RPW species from native sago and coconut pest, *R. vulneratus* (Azmi et al., 2017).

In a morphometric identification between RPW males and females, the significantly different characteristics in adult weevils were the rostrum length and the shape of the front tibia and pygidium (Wahizatul et al., 2012). The varied black spot pronotal markings commonly observed on the insect could not be relied on an identification mark. Consequently, other features (molecular analysis) should be considered.

A molecular analysis was conducted to assess genetic variations of *R. ferrugeneus* and the out-group *R. vulneratus* sampled from six districts in Terengganu, Malaysia (Chong et al., 2015). The study, which employed DNA amplification with mitochondrial cytochrome c subunit 1 (CO1) marker, successfully differentiated the species. The results also demonstrated no nucleotide base variations between the samples obtained from the different districts in Terengganu, indicating low genetic diversity. All the evaluated specimens also recorded a single haplotype, which was correlated to El-Mergawy et al.'s (2011) H8 haplotype. The observation suggested that the samples collected in Malaysia originated from the Mediterranean region.

In another report, a combination of cytochrome oxidase subunit I (COI) and cytochrome B (Cytb) data successfully distinguished *R. ferrugineus* from *R. vulneratus*. The time divergence assessment performed during the study recorded an earlier divergence of *R. vulneratus* than *R. ferrugineus* (Aman-Zuki et al., 2021). The findings demonstrated the possibility of *Rhynchophorus* species determination via several molecular analysis methods.

Several reports on pest infestation determination recorded effective RPW luring with pheromone traps. In a five-year study (2007–2012), RPWlure was employed in India and Ferrolure in Costa Rica to trap RPW (Idris et al., 2014). The RPWlure documented 80% of success, while the Ferrolure recorded 96%. Furthermore, 60% of *R. vulneratus* and 40% of *R. ferrugineus* were trapped in oil palm sampling areas. No damage symptoms were observed on the trees infested with the pest.

RPW trapping study conducted in coconut cultivation areas utilising pheromone (ferrugineol) and pineapple baits recorded the highest RPW trapped, followed up by other pheromone and bait combinations (Azmi et al., 2014). Despite the high numbers of RPW caught, pheromone and pineapple or sugarcane bait was costly and required twice weekly change compared to when employing sago palm bait. Daily rainfall also negatively affected the number of RPW trapped. Azmi et al. (2017) suggested that pheromone trapping was effective for RPW. Nonetheless, the approach was labour-intensive, expensive, could induce resistance, and risk environmental harm.

Haris-Hussain et al. (2020) reported that the highest attractant for adult RPW was pineapple, while the lowest was oil palm. The laboratory experiment utilised several baits, either synthetic or natural. The highest responses were documented by female RPW at almost 65% compared to male RPW. In another kairomone-releasing food bait assessment performed in a Terengganu field, Muhammad Firdaus et al. (2020) documented that 12 adult RPW per trap were caught with pineapple bait, which was the highest. Oil palm petiole trap recorded high adult RPW trapped at almost 11 per trap. The oil palm petiole caught more RPW than other baits employed, sugarcane, coconut, and control, demonstrating that RPW preferred oil palm petiole (Firdaus et al., 2020). The study also reported female RPW as the most caught for all baits at almost 76%. The experiment provided new information regarding the possibility of RPW preference for oil palm, hence requiring further monitoring.

Entomopathogenic fungi (EPF) have been studied as a potential RPW management technique in Malaysia. A preliminary investigation by Wahizatul et al., (2013a) isolated 43 fungi from adult RPW, including *Acremonium* sp., *Aspergillus* sp., *Cladosporium* sp., *Curvularia lunata, Geotrichum*sp., *Penicillium citrinum, Trichoderma* sp., and several unidentified species. *Aspergillus flavus* recorded the highest occurrence, approximately 26%, and most of the fungi detected were saprophytic. Potential pathogenic insect fungi were *Aspergillus*, *Curvularia*, and *Penicillium,* with 15 other fungi requiring further identification for potential EPF application (Wahizatul et al., 2013a).

Lin et al. (2017) reported the isolation of seven strains of fungus, which were named MetGra-1 to 7. The study employed *Tenebrio molitor* as soil bait and was conducted in Terengganu, the epicentre of RPW occurrence. The isolated strains were of the *Metarhizum anisopliae* species. The fungi were also evaluated against adult RPW for pathogenicity. MetGra-4 and MetGra-7 documented pathogenicity against the weevil, resulting in mortality within four and five days post-treatment, respectively. Furthermore, at 19 and 20 days, the total deaths of the inoculated RPW caused by MetGra-4 and MetGra-7, while the other strains recorded 0–60% mortality.

The MetGra-4 was assessed with molecular analysis, identifying the fungus as *M. anisopliae* (Ishak et al., 2020). The fungus spores were mass-produced to enable pathogenicity evaluations against adult RPW. Resultantly, 85% spore viability led to 92% total RPW infection with lethal time (LT_{50}) to kill 50% of the RPW population at almost nine days, while the lowest spore viability, 39%, documented an LT_{50} of 21 days. The MetGra-4 strain also exhibited virulent and infective properties on RPW 21 days after treatment. The report demonstrated the possibility of controlling the RPW population in Malaysia through EPF, where the approach caused high mortality of the weevil. Nonetheless, further research is necessary to mass produce the fungicide for effective delivery to the target organism, especially the RPW larvae commonly deposited inside palm stems.

4 Conclusions

The current bagworm management methods, which are equipped with the latest biopesticides and integrated with machinery, could curb outbreaks to a minimum amplitude below the threshold level. Nevertheless, Malaysian planters are concerned of the emergence of invasive alien RPW species currently affecting the subsidiary coconut industry. The pest could lead to a devastating impact to the oil palm plantations in the country if not monitored. Preventive measures and detection and management steps are necessary before host shift occurrence. Biopesticides may eliminate the damaging pest, and further studies would contribute to the successful pest management of the coconut industry and offer safety to other commodities in Malaysia.

Acknowledgements The authors would like to express their sincere gratitude to Dr Ramle Moslim and Mr Saharul Abillah Mohamad for their guidance, comments, and support throughout this study.

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Biology, Damage Caused, and Management of Thrips (Thysanoptera: Thripidae) Infesting Vegetable Crops in Malaysia

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Abstract Thrips (Thysanoptera: Thripidae) are regarded as one of the most pernicious insect pests that afflict vegetable crops across the globe. They cause damage to plant tissues during the pre-flowering to flowering stages, with the most harm occurring to pollen and flowers. The insect undergoes a gradual type of metamorphosis with six developmental stages: an egg, two active larval stages (L1 and L2), an active and non-feeding pupal stage (pre-pupa and pupa), and an adult stage (male and female). Both nymphs and adults can cause direct damage to vegetable crops through feeding and oviposition and indirect damage through the transmission of tospoviruses. Vegetables that are damaged due to infestation of thrips or viral diseases can become unmarketable, leading to financial losses to the producers. Control of thrips is mainly reliant on synthetic chemical pesticides, although alternative measures such as cultural, biological, and botanical controls have been reported to be promising and safer.

Keywords Biology · Malaysia · Management · Thrips · Tospovirus · Vegetable

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https://doi.org/10.1007/978-3-031-59268-3_2

1 Introduction

Vegetables account for 15% of daily food intake in Malaysia and provide job opportunities for farmers (Jipanin et al., 2001). The most commonly grown vegetables in Malaysia are cabbage, lettuce, tomato, leaf mustard, long bean, cucumber, water convolvulus, spinach, chili, and okra (Mohamed & Rokiah, 2006). Many vegetable crops suffer from insect pests that can cause major yield losses. These pests include caterpillars, beetles, aphids, whiteflies, mites, and thrips. Thrips (Thysanoptera: Thripidae), identified as a particularly problematic pest that targets vegetable crops, can be especially devastating (Tan et al., 2016). Thrips are tiny insects, ranging in size from 0.1 to 15 mm, and can be found worldwide. They have two pairs of wings that are fringed with cilia and have bristles on the veins. Their bodies are slender and elongated, and they come in a range of colors from light to dark, including some intermediate morphs (Mound, 2005; Palomo et al., 2015).

Numerous studies have identified *Frankliniella occidentalis* (Per-gande), *Thrips palmi* (Karny), and *Thrips tabaci* (Lindeman) as the primary pests in cucumber, pepper, tomato, onion, and zucchini. Thrips pose a significant threat to plants worldwide, as they not only cause direct damage during feeding and oviposition but also transmit plant viruses such as tomato spotted wilt virus (TSWV) and the impatiens necrotic spot virus (INSV). The consequences of their feeding activity can result in deformities, discoloration, and reduced yield, which can cause considerable economic losses (Ng & Zaimi, 2018). Unfortunately, the quarantine risks associated with these thrips species have been shown to have a negative impact on the global vegetable trade (Kumar et al., 2013; Palomo et al., 2015).

While thrips can cause substantial harm to vegetable crops, there appears to be a dearth of information regarding their presence in commonly cultivated vegetables in Malaysia. The available research on thrips and their impact on vegetable crops is scarce and largely restricted to their identification and distribution within the country. Nonetheless, the presence of *T. palmi, Thrips parvispinus, Megalurothrips usitatus, Thrips hawaiiensis,* and *T. parvispinus* has been reported on certain vegetable fields (Tan et al., 2016). A comprehensive survey conducted in 2011 recorded a total of 32 species of Thripidae, with a significant number of them belonging to the genus thrips (Azidah, 2011). Meanwhile, a separate study conducted in Peninsular Malaysia also recorded 23 species of the same genus. These findings suggest a diverse population of Thripidae in the region and provide valuable insights into the distribution and abundance of these species (Mound & Azidah, 2009).

The primary method for controlling thrips is through the use of chemical pesticides (Merel et al., 2018). However, alternative approaches such as cultural techniques, natural enemies, botanicals, and fungal pathogens are also available (Chinniah et al., 2016; Cote & Day, 2015). Our objective for this paper is to provide a comprehensive review of past studies on the biology, economic importance, and management of thrips that affect vegetables specifically in Malaysia.

2 Taxonomy, Host Range, and Distribution

In 1744, De Geer designated the name *Physapus* for thrips. However, in 1758, Linnaeus renamed them Thrips, as documented by Hamaseh (2011). The order Thysanoptera has been divided into two suborders: Terebrantia and Tubulifera. The order encompasses nine families, with the largest being Phlaeothripidae followed by Thripidae (Iftikhar et al., 2016). Family Thripidae is divided into 4 subfamilies, of which special attention has been given to the members of the subfamily Thripidae because they are the most economically important pest species (Ng & Zaimi, 2018). The Thripidae family encompasses a staggering 20,000 recognized species and can be found throughout the globe wherever vegetation thrives (Sartiami & Laurence, 2013). With around 6,200 species in existence, thrips are ubiquitous insects that inhabit forests, grasslands, bushes, leaves, and flowers and are distributed across both tropical and temperate zones (Iftikhar et al., 2016; Ng & Zaimi, 2018).

In Malaysia, the data on thrips distribution are not much. However, (Mound & Azidah, 2009) provided a key to the 23 species of the genus Thrips recorded from Peninsular Malaysia. Meanwhile, there are about 92 known species of Thripidae family recorded based on the checklists on thrips in Peninsular Malaysia, and this includes 17, 6, and 63 species from subfamilies Panchaetothripinae, Sericothripinae, and Thripinae, respectively (Azidah, 2011; Mound & Azidah, 2009; Ng & Zaimi, 2018; Ng et al., 2014). Thrips species in the genus, *Frankliniella* which is believed to be an invasive thrips species, have been found to be abundant in highland areas (Tan et al., 2016).

There is limited data available on the distribution of Thrips in Malaysia. However, 23 species of the Thrips genus from Peninsular Malaysia have been documented (Mound & Azidah, 2009). According to checklists of thrips in the region, there are approximately 92 known species in the Thripidae family, including 17, 6, and 63 species from the subfamilies Panchaetothripinae, Sericothripinae, and Thripinae, respectively (Azidah, 2011; Mound & Azidah, 2009; Ng & Zaimi, 2018; Ng et al., 2014). Notably, the invasive thrips species Frankliniella appears to be thriving in highland areas (Tan et al., 2016).

The thrips have a wide range of plant hosts, frequently feeding on them, which can deform and stunt the plants (Riley et al., 2018). Western flower thrips target various vegetable crops including cucumber, onion, pepper, potato, lettuce, and tomato (Capinera, 2001). These species of thrips are important for pollination of the plants they feed on, as they feed on flower tissues and pollen (Eliyahu et al. 2015; Suetsugu et al., 2019).

3 Biology of Thrips

Generally, members of the Thripidae family have a characteristic life cycle that consists of an egg, 2 active feeding larval instars, 2 relatively immobile non-feeding pupal instars, and adult stages (Eliyahu et al., 2015; Mound, 2018; Reitz, 2009). One of the major factors affecting the rate at which thrips develop is temperature. The number of degree days required for most of the genera of *Frankliniella* to complete one generation (egg to adult) is demonstrated to be 234 (lower threshold 10.5 °C) and 253 (6.5 °C), respectively (Riley et al., 2018).

Thrips are reported to be haplodiploid; that is, males have half the number of chromosomes (haploid number) and the other half (the diploid number) found in females (the diploid number). Males thrips are usually smaller than the females and are produced from unfertilized eggs (Parthenogenesis) (Funderburk, 2009).

3.1 Eggs and Larvae

Female thrips lay bean-shaped eggs inside leaves or floral parts of plant tissue (McLeod, 2008). The eggs take about 3 days to hatch, after which two nymphs emerge and start feeding on the plant (Cote & Day, 2015). These nymphs go through two larval stages, L1 and L2, which can last anywhere from 2 to 13 days, depending on the species (Cook et al., 2011). For instance, onion thrips (*T. tabaci*) take about 1.95 ± 1.42 and 4.12 ± 0.92 days to complete their first and second larval instar stages, respectively (Pourian et al., 2009). Western flower thrips (*F. occidentalis*), on the other hand, take 2 to 3 days to complete their first instar stage, and their second larval instar can last from 3 to 4 days (Gill et al., 2015).

3.2 Pupa and Prepupa

In the larval feeding stages, the insect transitions to a mobile prepupal stage, where feeding ceases. Following this, the insect descends to the soil and enters the pupal stage after approximately a week, protected within a cocoon (Cook et al., 2011; Eliyahu et al., 2015). The development of both prepupal and pupal stages in onion and western flower thrips typically occurs within 1 to 2 days (Pourian et al., 2009; Zhang et al., 2007). Once the pupation process is complete, the adults emerge and begin to feed (Cote & Day, 2015).

3.3 Adult

Various species of thrips have distinct life spans as adults. Thrips can develop from an egg to an adult in less than 19 days when conditions are favorable (Sani & Umar, 2017). Meanwhile, the western flower thrips can complete their entire egg-to-adult life cycle in approximately 10 days at 80° F (Cote & Day, 2015). In a study on the life history of the western flower thrips by Zhang et al. (2007), *F. occidentalis*, on excised leaves of five vegetables—cucumber, cabbage, bean, capsicum, and tomato leaf—developmental times from egg to adult were found to be 9.22 ± 0.13, 10.19 ± 0.08, 10.42 ± 0.06, 12.15 ± 0.07, and 12.91 ± 0.04 days, respectively. Research conducted by Gill et al. (2015) found that onion thrips require around 20 days to develop from an egg to an adult. Adult thrips typically live for no more than 23 days. Meanwhile, adult *F. occidentalis* females have a lifespan of 4–5 weeks at a temperature of 30 °C and lay an average of 50 eggs (Riley et al., 2018). In contrast, adult *T. tabaci* females' longevity ranges from 16 to 42 days on garlic and 28 to 30 days on onion (Gill et al., 2015).

4 Damages and Losses Causes by Thrips on Vegetable Crops Feeding Damage

Thrips are phytophagous insects that cause direct damage to plants during feeding and oviposition. The damage is due to the mechanical action of their mouthparts (Tommasini & Stefano, 1995). Some species of thrips cause damage to a single ornamental and vegetable plant part of either flower buds, leaf buds, leaves, fruit, or flowers, while others attack two or more of these plant parts (Bruce et al., 1995).

Adult *F. occidentalis* have been reported to inhabit the flowers of tomato, pepper, and eggplant, where they feed on pollen and flower tissues (Funderburk, 2009). Of all the vegetable crops attacked by thrips, tomato is the most seriously injured crop through oviposition (Capinera, 2001). Female insects laying their eggs in plant flowers can result in unsightly dimples and holes on the leaves that may persist until the fruit reaches maturity (Funderburk, 2009). Conversely, a particular insect species known as *T. tabaci* exhibits a preference for feeding and oviposition on onion leaves, ultimately leading to lowered yields. While they generally do not inflict significant economic damage on potatoes, these insects have also been known to target sweet potatoes and mustard (Gill et al., 2015).

Nymphs and adult thrips use their piercing-sucking mouthparts to infest vegetable plants by feeding on plant tissues, which consequently interrupts and decreases the leaf's photosynthetic capability (Palomo et al., 2015). Flower thrips primarily feed on plant pollens and flower tissues (Riley et al., 2018). Infested leaves and flowers can become distorted, malformed, and silvery due to the loss of plant fluids (Cloyd, 2010). Improper control measures of *T. tabaci* can cause yield loss ranging from 6