

Oecophylla smaragdina (Hymenoptera: Formicidae): A Biological Control Agent of the Invasive Bagworms *Metisa plana* (Lepidoptera: Psychidae)

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Abstract

The invasive bagworm *Metisa plana* Walker (Lepidoptera: Psychidae) is the dominant pest defoliator of oil palm canopies, leading to substantial leaf damage and monthly yield losses of up to 43%. Standard control methods involved trunk chemical injection (TCI) and spraying of highly toxic pesticides (such as cypermethrin) affecting non-target species. We hypothesized that the introduction of a biological control agent (BCA), the Asian weaver ant (*Oecophylla smaragdina* F.) (Hymenoptera: Formicidae), would outperform the TCI in scale and revenue consistency by controlling the bagworm population. A BCA colony was introduced with 20 brood nests translocated into four-hectare allocated experimental plots in Felda plantations, Peninsular Malaysia. To address the nuisances caused by BCA bites, we hypothesized that the essential tea tree oil (TTO) (*Melaleuca linariifolia* var. *alternifolia*) (Myrtales: Myrtaceae) repellency properties are a potent preventive measure. The assessment of ant-occupied palm trees shows an absence of foliar injury with higher quality fresh fruit bunches (FFB) and oil extraction rate (OER), contrasting with the high bagworm density in unoccupied, critically damaged canopies. BCA stands out as the most productive and lucrative, with more than triple the annual yield, incomes of any TCI group. Given the high correlation between yield variables and income, the polynomial regression showed accuracy in modeling BCA and TCI with minimal deviation between actual and predicted annual income. The repellent effect of TTO instantly neutralizes weaver ant aggressiveness, having an hour long lasting effect (first breakthrough report). Our findings suggest that *O. smaragdina* is an effective alternative to pesticide control treatment of bagworms.

1. Introduction

Playing a significant role as indigenous leaf-eating pests of the African oil palms (*Elaeis guineensis*) Jacq. (Arecales: Arecaceae), in Malaysia and Indonesia (Kamarudin et al., 1994), the bagworm, *Metisa plana* Walker, is identified as the most dominant destructive pest species (Ting et al., 2023; Syarif et al., 2023). The defoliation induces a decrease in photosynthesis rate, hence lowering monthly and yearly yield production (Enting & Latip, 2021), reaching a fresh fruit bunches (FFB) average loss of 10 tons per acre (Kalidas, 2012). Moderate defoliation (10–13%) by bagworms can result in a 30–40% decrease in yield (Mohd Johari et al., 2023), but more severe infestations can cause up to 43% yield loss (Adhawiyah et al., 2023; Basri et al., 2022). The economic losses exceeded USD 25 million yearly (Che Hussian et al., 2025). Thus, the damage caused by the invasive *M. plana* species is likely to become more widespread without proper control measures (Wood & Norman, 2019a; Wood & Norman, 2019b). In 2013, bagworms were officially classified as quarantine pests in Malaysia (Kamarudin et al., 2017). To eliminate this pest, broad-spectrum, long-lasting contact pesticides (Cypermethrin and deltamethrin are highly toxic) have been used (Wood & Norman, 2019a). This led to an ecological disaster, marked by the indiscriminate suppression of beneficial insects and the accumulation of chemical hazards in agricultural soils and the environment, contributing to the development of pesticide resistance among target species (Wood & Norman, 2019b). An alternative, cheap, and environmentally friendly method of control is necessary. The Asian weaver ant (*Oecophylla smaragdina* F.) has controlled over 50 pest species across 12 diverse crops (Way & Khoo, 1992; Peng et al., 2012a). Its effectiveness as a biological control agent has been

compared with pesticides in Southeast Asia and Australia (Van Mele & Cuc, 2000; Peng & Christian, 2005a). Bagworm infestations are critical in unoccupied weaver ant palms (Exéllis & Idris, 2013). In unoccupied plantations, collected brood nests are translocated to rear incipient colonies in the outbreak-affected plants (Offenberg et al., 2013). Introducing new nests to boost incipient colonies in affected areas is a documented effective method (Exéllis et al., 2023a, b). The ants' major workers engage in daily predation through extensive foraging and territorial behaviour (Exéllis et al., 2024; Exéllis et al., 2025a). Their bites, resulting in the rejection of using Asian weaver ants as a biological control agent (BCA) in some cases (Van Mele, 2008; Van Mele et al., 2009; Offenberg, 2015). Some plantation workers even resorted to burning ants' nests or exterminating them with poisons (Exéllis et al., 2023a). Therefore, we propose and hypothesize that the tea tree (*Melaleuca linariifolia* var. *alternifolia* (Maiden & Betche) essential oil is a potential repellent of weaver ants (Chailleux et al., 2019). Assuming an output shows a high R^2 (variance proportion) and relatively low Root Mean Squared Error (RMSE), we hypothesized that the combination of Average Yield, Oil Extraction Rate (OER), and Total Yield can successfully predict income with some nonlinear adjustments using a polynomial regression. This study assesses (1) the ability of weaver ants to control bagworm populations by comparison with the trunk chemical injection (TCI) method. The efficiency levels were measured based on various productivity parameters, i.e., foliar injury level, monthly fresh fruit bunches (FFB) yield, and OER relating to grade quality. In addition, we assess (2) the effectiveness of the tea tree oil (TTO) essential oil as a treatment for (i) bite protection, (ii) repelling the Asian weaver ant, and (iii) determining their long-lasting effect.

2. Materials and Methods

2.1. Study sites and plot selection

This study was conducted in oil palm plantations located in Felda Gunung Besout, Perak, Malaysia, from 2019–2022 (N03°49.408' E101°19.775' and 3°50'30" 101°18'08" E; Supplementary Fig. 1). The total plantation's area is 1064.53 ha, and it was further divided into 4-ha plots allocated to 266 smallholders. The oil palm plots were selected based on: (1) the presence of bagworm, and (2) the ongoing control treatment by trunk chemical injection (TCI) method. The FFB yield fluctuates with the palm age differences (Zabid et al., 2018). Hence, to avoid biases, the selected plantation area had oil palm trees of the same age (six years old and 3–5 meters high). The study area was selected by the purposive random sampling method, comprising palm trees affected by bagworms and treated with TCI (Fig. 1A-D; Supplementary Fig. 2A). Four plots (four replicates) were established in 4 ha plantations each for TCI, except for the Federal Land Development Authority (FELDA) allocated weaver ant experimental plot of one 4 ha plantation. Three types of plots were established: (i) control plot (not treated by any measures), (ii) plot treated by TCI, and (iii) plot treated by the Asian weaver ant as a biological control agent (BCA). Plots were monitored monthly to record the rate of damage done by bagworms and associate this damage with oil palm productivity/ quality by measuring and recording; (i) foliar injury level, (ii) monthly FFB yield, (iii) oil extraction rate (OER) preluding to fruits grade quality and (iv) the monthly incomes (Ringgit Malaysia RM). The foliar injury level was classified following Exéllis & Idris's study (2013; Exéllis,

2014). The control plot produced fresh fruit bunches of low quality, rejected by mills processing factories. The palm tree canopies became skeletons (deprived of green leaves) (Fig. 1A; Supplementary Fig. 2A).

2.1.2. Incipient ant colonies rearing – Colonies expansion set up

We have two categories of Asian weaver ant rearing protocols and manipulation. First is rearing naturally by planting citrus tree species, the Calamansi tree (*Citrus microcarpa*) Bunge. (Sapindales: Rutaceae) (Supplementary Fig. 2B) known to attract newly mated mature queens (green colour). In this case, a new colony can reach maturity by 24–36 months of growth (Peng et al., 2012a; Exéllis et al., 2025b). Such colonies can be translocated to bagworms affected oil palm tree canopies to eradicate the infestation. Second is artificially rearing a colony by capturing a mature brood nest to place it at the top middle position of an affected bagworm oil palm tree trunk between the fronds (Supplementary Fig. 2A, red arrow). The translocated brood nest develops into a stable colony within one month, with the appearance of two more nests on average (Exéllis et al., 2025b).

Weaver ants poorly colonized the study area. Twenty brood nests were collected from the Calamansi orchard inside the oil palm plantation (Supplementary Fig. 2B-C). The orchard serves as a buffer zone promoting the growth and expansion of the weaver ant's incipient colonies (Lim, 2007). The collection of brood nests (from mature colonies) was carried out preferably during rainy days, as this corresponds with the emergence of many reproductive individuals (Van Mele & Cuc, 2007; Nielsen et al., 2016; Exéllis et al., 2025a). During the lowest activity period of the weaver ant (sunrise), a single nest is cut from the tree (less than 2 meters high) (Peng et al., 2012b; Exéllis et al., 2024), sealed tightly fast inside a large, hard fertilizer bag. We manipulated four highly *M. plana*-affected (level 4) tagged plots of 1 ha each (Supplementary Fig. 3A-B) by posing and fixing the *O. smaragdina* nests at the median side of the canopy base between the palm fronds for stability (Supplementary Fig. 2A). To avoid direct exposure to strong winds, each nest was placed at the lowest side of the canopy in the center for stability and to preserve nest integrity (corresponding to the top of the palm trunk tip) preferably three meters above the ground to resemble natural nesting site position (Crozier et al., 2010; Exéllis et al., 2025b). The nest was directly exposed to the morning light to promote nest building, foraging, and brood rearing. Each brood nest covers an average of 10 palm trees with an average range of 30–85 total nests per colony (Exéllis et al., 2023b; Exéllis et al., 2025b) by establishing the artificial Line Bridge network to interconnect each canopy to one another (Peng et al., 2004). This method facilitates the major workers' exploration crossover, promoting the colony's expansion to adjacent palm canopies. Foragers initiated new nest construction within 24 hours (Supplementary Fig. 4A). Such colonies and workers will initiate fast nest construction and establishment (Offenberg, 2015). To enhance the possibility of trapping mated queens after rain (Nielsen et al., 2016; Nene et al., 2016a), an artificial nesting network was established with natural palm frond leaflets (Offenberg, 2014) (Supplementary Fig. 4B). All bent palm fronds used to construct artificial trap leaflets nests (by binding them together to imitate the weaver ant nest

construction technique), never returned to their initial high position. The higher canopy side nest location is significantly more suitable for attracting *O. smaragdina* queens (Rwegasira et al., 2015). The height above the ground defining the nest location in the canopy was fixed at an average of 4 m (Exéllis et al., 2025b). Honey and sucrose water (20% concentration), along with chicken intestines (as a protein artificial supplement booster), were provided once a week during one month (Peng et al., 2004; Nene et al., 2016b). To establish a strong *Oecophylla* colony, one planted host plant (Calamansi, citrus tree) per colony is necessary. To sustain one Asian weaver ant colony occupying an average range of 8–12 oil palm trees, a single favorite host plant (citrus tree) is sufficient (Exéllis et al., 2025b). This information helps to know the number of brood nests needed to be translocated to any affected bagworm oil palm plot based on the total number of planted trees for further biological control application. If an area is planted with 100 oil palm trees, deploying 10 brood nests is sufficient protection for the targeted trial area. Since weaver ants are a territorial species, two palm trees were left empty between plots to prevent future fighting between distinct colonies.

2.3. Evaluation of biological control compared to chemical control

The trials consisted of three components: control plots without the Asian weaver ant and the TCI, the biological control strategy, and trunk injection chemical treatment. We compared three experimental conditions between (1) *O. smaragdina*-occupied palm trees, (2) unoccupied palm trees consisting of the control plot critically affected by bagworms, and (3) the TCI treatment using two systemic insecticides, Krotofos 60 (monocrotophos 55% w/w) and multifos 60 (methamidophos 50 w/w), transported to foliage within hours to kill bagworms fast (Salim & Hamid, 2012; Salim et al., 2015b). Plots were monitored monthly to record the rate of damage done by bagworms and associate this damage with oil palm productivity/ quality by measuring and recording; (i) foliar injury level, (ii) monthly FFB yield, (iii) oil extraction rate (OER) preluding to fruits grade quality and (iv) the monthly incomes (Ringgit Malaysia RM). The foliar injury level was classified following Exéllis & Idris's study (2013; Exéllis, 2014). The control plot produced fresh fruit bunches of low quality, rejected by mills processing factories. The palm tree canopies became skeletons (deprived of green leaves) (Fig. 1A).

2.4. Bite protection – Repellency – Long-lasting effect (TTO)

The study was carried out following the purposive random sampling method. The host plant occupied by weaver ants in Felda Besout, Perak, Malaysia, and Banyuwangi, Indonesia, was selected. The trials were performed on large major workers (experimental unit), known to be more ferocious than smaller workers (Lim, 2007; Exéllis et al., 2025a; Exéllis et al., 2024), to evaluate the impact of pure organic tea tree essence oil extract drops to observe any nausea or escape reaction. The chemical originated from the Thursday Plantation Tea Tree Oil (TTO Australia), 100% pure organic, with a standard bioactive composition, under an act regulated by the ISO standard 4730. Weaver ant aggressive behavior (a 90° angle gaster elevation, Supplementary Fig. 7) was verified by placing the fingertips on the barrack nest of

an occupied Indonesian Bayleaf tree, “Pohon Salam”, *Syzygium polyanthum* Walp. (Myrtales: Myrtaceae) in Banyuwangi, Indonesia (8°27'19.4" S 114°07'05.7" E) (Supplementary Fig. 6b-c). The nest was disturbed by shaking it to create an emergency response from the colony's major workers. The control test was done directly by human presence without the TTO chemical. A preliminary test was carried out on 3 distinct colonies foraging trails at the base trunk by placing a filter paper disc treated with one pure drop of tea tree oil (TTO). All three replicates reacted positively by avoidance of the filter paper disc (N = 10). As ants quickly showed rejection, a further test was conducted on the human body. One pure drop of TTO was applied to the hair, neck, arms, and legs of the ant-exposed human observer (first author), and was tested to verify its repelling effect on other *O. smaragdina* colonies. The task involved positioning oneself at a very close distance (an average of 10 cm) from the main tree branches and placing the hands and arms on the weaver ant nests. We recorded the avoidance and biting behavior on an occupied single tree for each colony (N = 10). The effect of the essential oil was evaluated immediately after application to the hands and wrists, then at 15, 30, 45 minutes, and one hour to verify contact persistence during the daily activity peaks corresponding to the hotter periods (1100 to 1530 hours). The experiment was repeated three times (See the two videos of the test from the Mendeley data link <https://data.mendeley.com/datasets/y4znm8mgz3/3>, titled disturbed nest and tea tree pure extract repellency test).

2.5. Statistical analysis

2.5.1. BCA versus TCI data

The data set was pooled due to its large sample size (2019–2022), which presented a skewed and kurtotic distribution, described as being more suitable (Kim, 2013). It was then summarized using descriptive statistics and is considered more accurate to replace the Shapiro-Wilk and Kolmogorov-Smirnov tests for large sample data (Kim, 2013). Since the data variable response (income) is right-skewed, did not follow a normal distribution (Limpert et al., 2001; Guisan et al., 2002; Coupé, 2018; Hastie, 2017), the Generalised Additive Model (GAM), flexible on the normality assumption (Wood, 2017), was applied with the link function identity and follows Exélis et al's method (2024). The response variable (*Income*) in this study is not normally distributed. Hence, GAM is applied with a gamma distribution using a log link function, which handles skewness naturally and ensures positive predictions (Kim, 2013; Coupé, 2018). The GAM algorithm is being used for agricultural traits, such as wheat yield, and for solving problems like pest assessment, providing satisfactory insight into predictive events alongside factual ones (Marcillo et al., 2021). The income data for five estate groups—TCI OPP I to IV and BC Ants—was analyzed using a second-degree polynomial regression model, incorporating a total of three predictors: Average Yield, OER (Oil Extraction Rate), and Total Yield. The modelling is performed on two predictor variables to obtain three distinct models, taking the incomes as the response factor. In model 1, the income is evaluated with the average yield and total yield metrics. Models 2 and 3 evaluated the combination of average yield and OER, then total yield and OER, respectively. Each model is subjected to an evaluation based on the Degree of Freedom (df), and the Akaike Information Criterion (AIC). To evaluate the adequacy of the GAM model with a Gamma distribution, AIC values are compared

– the lower the AIC, the better (Rubec et al., 2016). The best model is also selected based on the significance of predictors, using a p-value threshold of 0.05. All the possible models are summarized, and the best among them is chosen based on evaluation metrics of the R-sq (adj), deviance explained, p-values, and AIC values (Table 1).

X_1 : Average_Yield_permth_ha; x_2 : Total_Yield_ton_perhectar; x_3 : dt\$OER_percent and y : Incomes_RM. This method allowed for capturing non-linear relationships between the variables, average, total yield, and OER with the generated incomes. 240 observations of data were collected each year, totalling 960 records for four years (2019–2022).

2.5.2 Tea Tree Oil evaluation

In this analysis, a logistic regression model with a binomial distribution and a logit link function is used to examine the relationship between the Bite variable (Bite = 1, No Bite = 0) as the response, and the Repel variable (Repel = 1, No Repel = 0) as the predictor. The logit link function used is defined as:

$\text{logit}(p) = \frac{p}{1-p}$, $p(0,1)$. Where log is the natural logarithm (base e), and $\frac{p}{1-p}$ is called the odds of the event, and p is the probability of the event.

Both the response and predictor variables are in binary form. Receiver Operating Characteristic (ROC) is a graphical tool used to evaluate the performance of a binary classification model, such as logistic regression. It assesses how well the model distinguishes between two classes (e.g., Bite = Yes/No) and is useful when class distribution is imbalanced. A confusion matrix was performed to compare the observed outcomes to the model's predicted outcomes. We performed all statistical analyses using R version 4.3.3 (R Core Team, 2024).

3. Results

3.1. *Oecophylla*-bagworms census

Ants could neutralize *M. plana* larvae (N = 30) approaching their protected zone under darkness close to ant nests. The results of the monthly surveys provide this information (Supplementary Tables 1 and 2). The censuses provide information on the level of foliar injury and bagworm density, demonstrating the differences between occupied and unoccupied oil palms observed in the focused study area (Figs. 1A-F; Supplementary Table 2). It is important to note that only the larval stage is responsible for foliar feeding, causing injury. The red arrows indicate the distribution of brood nests at the top-level positions of several palm tree canopies, ranging from 5 m to 7 m in height (Fig. 1E-F). Nests exhibit a well-constructed network with a prominent presence of heavy, whitish silk that closes off all exits (highlighted by the black arrow) (Fig. 1E-F). In contrast, the palm fronds in occupied blocks appear healthy, with little to no observable injuries.

3.2. Experimental results: Trunk chemical injection versus biological control agent

The performance of the five plantation groups—BC Ants, TCI OPP I, TCI OPP II, TCI OPP III, and TCI OPP IV—was assessed based on key indicators, including average yield, oil extraction rate (OER), total yield, and income (Supplementary Table 4–2019 to 2022). Biological control ants are the best performers with the highest median of total yield per hectare, with maximum and minimum yields, but still very much higher than the TCI OPP yield. For TCI, TCI OPP IV has the lowest median of yield per hectare. Both TCI OPP I and TCI OPP II have almost the same median of yield per hectare (Fig. 2A-D). Box plots are used to compare the median and variability of the data spread for average yield per month, total yield per hectare (ton), OER percentage, and income across the BCA and TCI groups. In most cases, the BCA group shows the most consistent variability, as the IQR values of the predictors (x_1 , x_2 , x_3) are smaller than those of all the TCI groups (Figures A–C). Figure D shows that the median income for the BCA group is significantly higher than that of the TCI groups.

We summarize the performance of all groups to expose the overall results, showing a similar trend over four years. BC Ants significantly outperformed all TCI groups. With an average monthly yield of 15.50 t/ha and the highest OER (19.62%), BC Ants achieved the highest total yield (766.17 t) and total income (RM 327,430.76). The average monthly income for BC Ants was RM 27,285.90, more than triple the income of any TCI group. TCI OPP I and II performed moderately well, with yields of 4.89 and 4.56 t/ha/mo, respectively. The OERs were consistent with other TCI groups (~ 17.7%), and their total incomes were RM 99,034.96 and RM 92,401.12. While they lagged significantly behind BC Ants, they maintained a moderate productivity level compared to the lower-performing TCI groups. TCI OPP III and IV displayed the lowest performance across all metrics. Their average yields were below 3.6 t/ha/mo, with monthly incomes under RM 6,000. This trend prevailed for the four years of treatment. The polynomial regression showed a high degree of accuracy in modeling estate income, indicated by an R^2 score close to 0.99, suggesting that the model explains almost all variability in the income data. The Root Mean Squared Error (RMSE) shows low values across estates, implying minimal deviation between actual and predicted income (Supplementary Fig. 5A-D). BC Ants consistently recorded the highest average yield and total yield, resulting in significantly higher income values compared to TCI groups. TCI's performance also showed less month-to-month variability. The income data for the four TCI OPP estates (I–IV) and BC Ants estate over the years 2019 to 2022 shows noticeable differences in income levels, growth patterns, and volatility. All four TCI OPP estates demonstrate a generally increasing income trend from 2019 through 2022. However, the increases are modest when compared to BC Ants. BC Ants consistently records income figures far above the TCI OPP estates each year (Supplementary Tables 4 & 5; Figs. 5A-D). For instance, in 2020 and 2021, its monthly average often exceeded 30,000 while others stayed below 15,000. Despite its higher values, BC Ants displays a stable trend with relatively small variance month to month. The GAM evaluation shows that the income is positively associated with the three predictors, average, total yield and OER (Fig. 3). The graph in Fig. 3 shows the fitted income generated from the best model and the actual income. Graphically, it is observed that the actual data is clustered close to the predicted model (straight line). Hence, the fitted income data exhibited close similarity with the actual income data. The model x_1 , x_3 appears as the most fitted with lowest AIC (Table 1, supplementary Table 5). The minimum income (RM 5064), and max income (RM

94,000), the error is only 9,000l; this is very good results (Supplementary Table 4). The variables x_1 and x_3 are significant predictors (p -value < 0.05) for predicting income. Based on the deviance explained value, 89.1% of the variation in income can be explained by the model that includes only x_1 and x_3 , in line with the principle of parsimony. Therefore, the full model, which includes all predictors, is not selected, as it is more complex without providing substantial improvement in model performance. The Generalized Additive Model (GAM) with a Gamma distribution and log link function provides a robust and well-fitting model for predicting income. The selected model includes two significant predictors (x_1 and x_3), both of which exhibit non-linear relationships with the response, as captured by the smooth terms. Diagnostic assessments, including residual plots, QQ plot of deviance residuals, and the deviance explained value, indicate that the model assumptions are reasonably satisfied. The model explains 89.1% of the deviance and achieves a high adjusted R^2 of 0.844, suggesting excellent explanatory power. Based on the principle of parsimony and statistical significance, this reduced model is preferred over the full model. Therefore, the fitted GAM is both statistically adequate and practically interpretable for modelling income data with a right-skewed distribution.

Table 1
Possible models of Generalised Additive Model with Gamma and log link function.

Predictor (s)	Significant predictor (P-value < 0.05)	DF	AIC	Adj.R2	Deviance explained
x_1	$x_1(0.0000)$	8.002	4857.652	0.838	84.4%
x_2	$x_2(0.0000)$	7.071	4863.224	0.811	83.3%
x_3	$x_3(0.0000)$	3.430	5090.171	0.556	57.9%
x_1, x_2	$x_1(0.0000); x_2(0.9150)$	9.025	4859.745	0.838	84.4%
x_1, x_3	$x_1(0.0000) ; x_3(0.0000)$	18.904	4789.762*	0.844	89.1%
x_2, x_3	$x_2(0.0000) ; x_3(0.0000)$	18.919	4798.618	0.817	88.7%
x_1, x_2, x_3	$x_1(0.0000) ; x_2(0.5910) ; x_3(0.0000)$	19.918	4791.485	0.843	89.2%
Note: DF-degrees of freedom, AIC – Akaike’s Information Criterion					
x_1 : Average_Yield_permth_ha; x_2 : Total_Yield_ton_perhectar; x_3 <- dt\$OER_percent					
y: Incomes_RM (response variable). *The best model					

3.4. Bite nuisance protection, repellency, and long-lasting effect: TTO

The major workers approached and climbed the hand posed on their nests. Whenever the tea tree essential oil was not used as a protective shield, a plethora of workers came instantly to bite relentlessly. In contrast, no ant bites were recorded during all the repeated tests carried out under tea tree oil spread throughout the hand and arm (N = 90 for three replicates) except for only one incidence (Fig. 4 – Bite over time). Few workers came to attack while the majority stood far from the hand. However, aggressive stances were exhibited by the mandible widely open with the gaster 90° angle elevation marking their territorial characteristic behavior in a swift response to the encroachment (Supplementary Fig. 6a, Fig. 7). The tea tree essential oil demonstrated a powerful repelling effect on the major workers causing avoidance and a rare bites absence behavior (Fig. 4). This oil possesses a deterrent odor, having the quality of residual contact persistence for up to one hour upon first application on the body (See the two videos of the test from the Mendeley data link <https://data.mendeley.com/datasets/y4znm8mgz3/3>, titled disturbed nest and tea tree pure extract repellency test). The very large negative coefficient value $\exp(-21.87) = 3.1 \times 10^{-10}$ is close to zero probability of a bite when repelled. Repel = 1 almost completely prevents bites. However, the huge standard error (7030) and p value = - .998 indicate that this result is not statistically significant. This is likely due to perfect separation and/or medium sample size. The area under the curve (AUC) is 0.98, which means the model has a 98% chance of ranking a randomly chosen "positive" case higher than a "negative" one (Fig. 5). That is excellent performance. In general, the model accuracy is 96%. The model correctly predicts most "No Bite" cases and does not miss any "Bite" cases. The precision is low (only 1 out of 3 predicted bites was correct).

4. Discussion

This study is the first applied research method conducted in a large open-field oil palm plantation to evaluate a biological control agent (BCA). The Asian weaver ant is well-documented for its effectiveness in dealing with diverse pests of economic importance that are harmful to commercial crops (Offenberg, 2015). Foliar injury is severe, with 462.30 cm² scraped and cut leaves representing 2.794 g of removed biomass by *M. plana* instar larvae (Tuck et al., 2010). The BCA treatment demonstrated the control of the invasive and poly-phytophagous bagworm over 4.5 yearly life cycle generations (average 75 days – Tuck et al, 2010; Enting & Latip, 2021), corresponding to 18 generations (over 4 years).

4.1. Control method impacts: productivity, quality, and yield-profit

4.1.1 Current method – Management cost (Ringgit Malaysia)

The current method of controlling bagworms includes injecting oil palm trunks with systemic organophosphate (which produces lethal effects on pests eating leaves) and aerial spraying of biopesticides (such as *Bacillus thuringiensis*). The protocol treatment includes pyrethroids (cypermethrin and deltamethrin) with selective pesticides (lead arsenate) and trichlorfon (Wood & Norman, 2019a;

2019b). Cypermethrin and deltamethrin are highly toxic to aquatic animals (Khompun et al., 2024), and their environmental persistence seriously threatens humans (Ullah et al., 2018). The cost induced by these methods is much higher than the usage of the Asian weaver ant. With an estimated RM 0.70 bagworm TCI cost per palm (Salim et al., 2015b) and a density of 136–160 oil palm trees per hectare, the average cost is RM 95,000.00 to RM 112,000.00 for a 1000-ha plantation during a severe infestation outbreak. *Bacillus thuringiensis* (Bt) aerial spraying by drones engages consequent investment that is not affordable by most of the smallholding plantation owners (Masri et al., 2022). Sticky traps using female pheromones to lure male individuals into the infested oil palm blocks generated a substantial decline in the male moth population, offered an affordable cost to smallholders (Norman & Othman, 2016; Mohd Najib et al., 2017; Noorhazwani et al., 2024). The information on the benefit-cost of pest control management and the study of pesticide persistence in the agro environment is scarce and limited in open field plantations (Muhamad et al., 2013; Sulaiman et al., 2020). The cost-benefit studies comparing *Oecophylla* BCA to conventional methods are scarce. Peng & Christian (2005b), and Offenberg et al (2013) are among the rare detailed evaluations with valuable information on this matter.

4.1.2 BCA versus TCI

The damages incurred by the bagworm on the unoccupied control plot without the TCI severely affected their FFB grade, resulting in all fruits being rejected and not acceptable for the mill palm oil processing industries. Defined by the OER level, the FFB grade was lower in TCI treatments, while the BCA treatment gave a significantly higher quality for the four years of data record. The significant increase in productivity, quality, and annual yield after the introduction of weaver ants is consistent with other reports from Australia (Peng et al., 2012a; Forbes & Northfield, 2017), the Philippines (Pag-Ong, 2021), China and Vietnam (Van Mele & Cuc, 2000; Peng et al., 2014), Thailand (Offenberg et al., 2013), Indonesia (Ridwan et al., 2019), and Africa (Van Mele et al., 2007). Peak yields tend to occur around March–May and September–November, aligning with bimodal rainfall seasonal patterns in tropical regions (Mumo et al., 2018). The biological control of fruit plantations using *Oecophylla* spp. has been well-documented in Australia and Asia (Krag et al., 2010; Peng & Christian, 2006; Peng & Christian, 2007). A study by Peng & Christian (2005b) demonstrated the higher yield and profit resulting from using Asian weaver ants compared to the relatively limited impact of chemical insecticides in Australian mango orchards. The cost-effectiveness of ant control and significant harvest incomes were also observed in Vietnamese citrus orchards. However, in Thai mango blocks, biological control failed due to fruit-setting destruction by the leafhopper *Idioscopus clypealis* (Offenberg et al., 2013).

4.2. The manipulations and deployment of weaver ant nests in oil palm plantations

Based on field experiences, capturing nests is most effective between 2200 hours and 0600 hours (Lim, 2007; Exélis et al., 2024). During this time, ants are slower, less aggressive, and less likely to launch aggressive attacks on intruders. Spending time under a palm tree with a heavy presence of *Oecophylla* nests can be challenging (Exélis et al., 2023b; Exélis et al., 2025b). It is possible to swiftly remove a single nest from a short palm tree and relocate it within the same plantation. Careful handling with

appropriate disposable materials is necessary when sampling brood nests that contain a high abundance of ant individuals across all castes. Introducing the captured nest on a new palm tree affected by bagworm defoliators, along with chicken, has proven effective. Transferring nests over long distances for biological control trials is not recommended. The newly introduced biological control agent could act similarly to an exotic species. Risks to human, animal, and plant health and potential environmental damages have been reported (De Clercq et al., 2011). Reduction of other natural native enemies is reported in multiple cases in both tropical and temperate climate countries (Van Lenteren et al., 2006).

4.3 Bite protection – Repellency – Long lasting effect (TTO)

An alternative approach to mitigate ant attacks is to employ natural insect repellents. *Melaleuca alternifolia* tea tree is a novelty, and few studies have reported similar breakthroughs from the application of oils to repel *O. longinoda* in Senegal (Chailleux et al., 2019). The essence oil's bioactive compounds (i.e., terpenes and tertiary alcohols) provide a strong defensive function to the plants, resulting in expelling insect intruders or causing mortality (Buteler et al., 2021). Generally, essential oils are vulnerable to demonstrating low persistence in the environment due to fast volatilization and oxidative degradation from heat and light (El et al., 2015). The Asian weaver ant's foraging activity disruption, causing instant bite nuisance nullity, is a breakthrough finding. TTO application on hands, neck, and head provided full protection from ant bite nuisance, repelled ferocious major workers with a long lasting effect (one hour). Venturing into territories dominated by *O. smaragdina* consistently resulted in ant bites and immediate aggression. Ecological damage incurred to the environment by synthetic pesticides is well documented, and the application of BCA throw selective natural enemies for augmentative biological control is becoming more widespread worldwide (Van Lenteren et al., 2018). The efforts to reduce reliance on manual human harvesters are timely (Radzi et al., 2023), hence minimizing ant bites.

5. Conclusion

The study discovered that maintaining a sufficient numerical ratio between weaver ant predator-defoliators and foragers, favoring the latter, facilitates the effective suppression of invasive bagworms. The healthy green foliage in occupied palms contrasted strongly with the skeletal sight of unoccupied canopies. The FFB productivity and quality improve with higher monthly incomes. The innovation of *M. alternifolia* tea tree essential oil as an aggressively effective weaver ant repellent vector opens new alternatives. The future adoption of the Asian weaver ant for better, and environmentally friendly, and cheaper cost pest management in the tropical agro-systems of Asia. Consequently, the study concludes that adopting Asian weaver ant colonies is a feasible and productive strategy that offers smallholders in the oil palm industry an affordable and effective means of controlling the invasive bagworm *Metisa plana*.

Declarations

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

SUPPLEMENTARY INFORMATION

The supporting information is provided in this manuscript.

FUNDING

DECLARATION

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Author Contribution

Exélis Moïse Pierre: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Prepared tables/figures, Project administration, Resources, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. Rosli Ramli: Project administration, Resources, Supervision, Writing – Review & Editing. Roslinazairimah Zakaria: Formal analysis, Methodology, Software, Visualization, Writing – Review & Editing. Azarae Hj Idris: Investigation, Project administration, Resources, Supervision, Writing – Original Draft. Rabha W. Ibrahim: Formal analysis, Methodology, Software, Visualization, Writing – Review & Editing.

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Data Availability

The data presented in this study are openly available in this manuscript and can be retrieved in the below link (Raw dataset BCA vs TCI and videos disturbed nest – tea tree pure extract repellence positive test): <https://data.mendeley.com/datasets/y4znm8mgz3/3>

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Figures

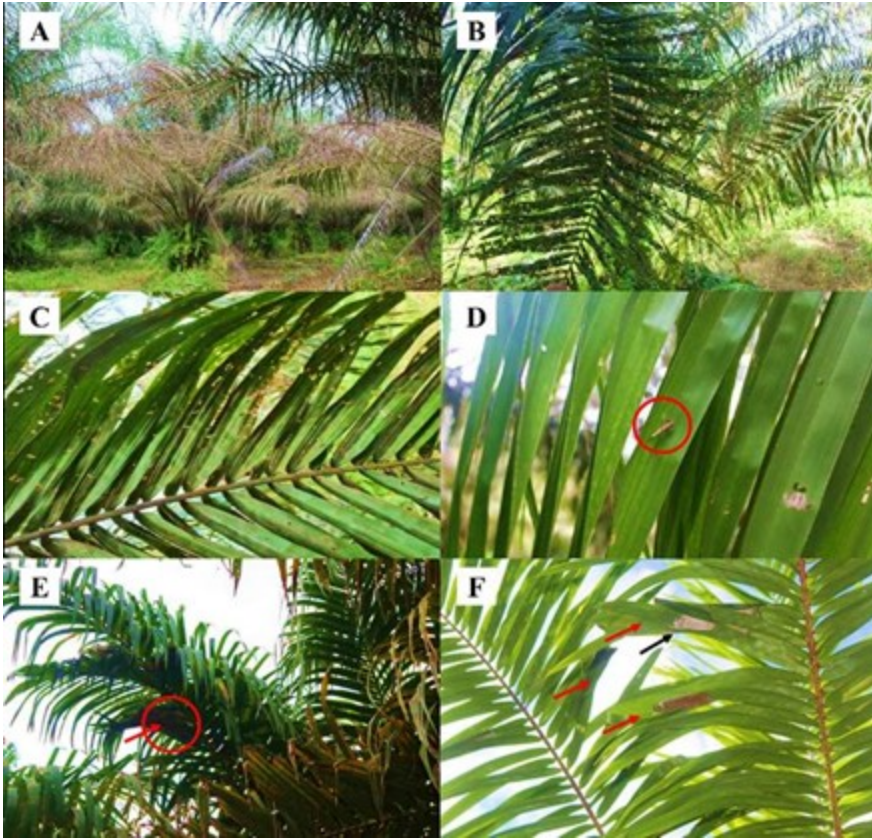


Figure 1

A-F. *M. plana* outbreak in Felda Besout, Perak. A- Foliar injury of level 4. B- Level 3. C. Level 2 and D- Level 1 with characteristic hook type *M. plana* pupae (red circle) at the adaxial side of the leaflet frond. E- *O. smaragdina* brood nests. F- The red arrows indicate the freshly constructed brood nests and the heavy presence of silk-whitish (black arrow).

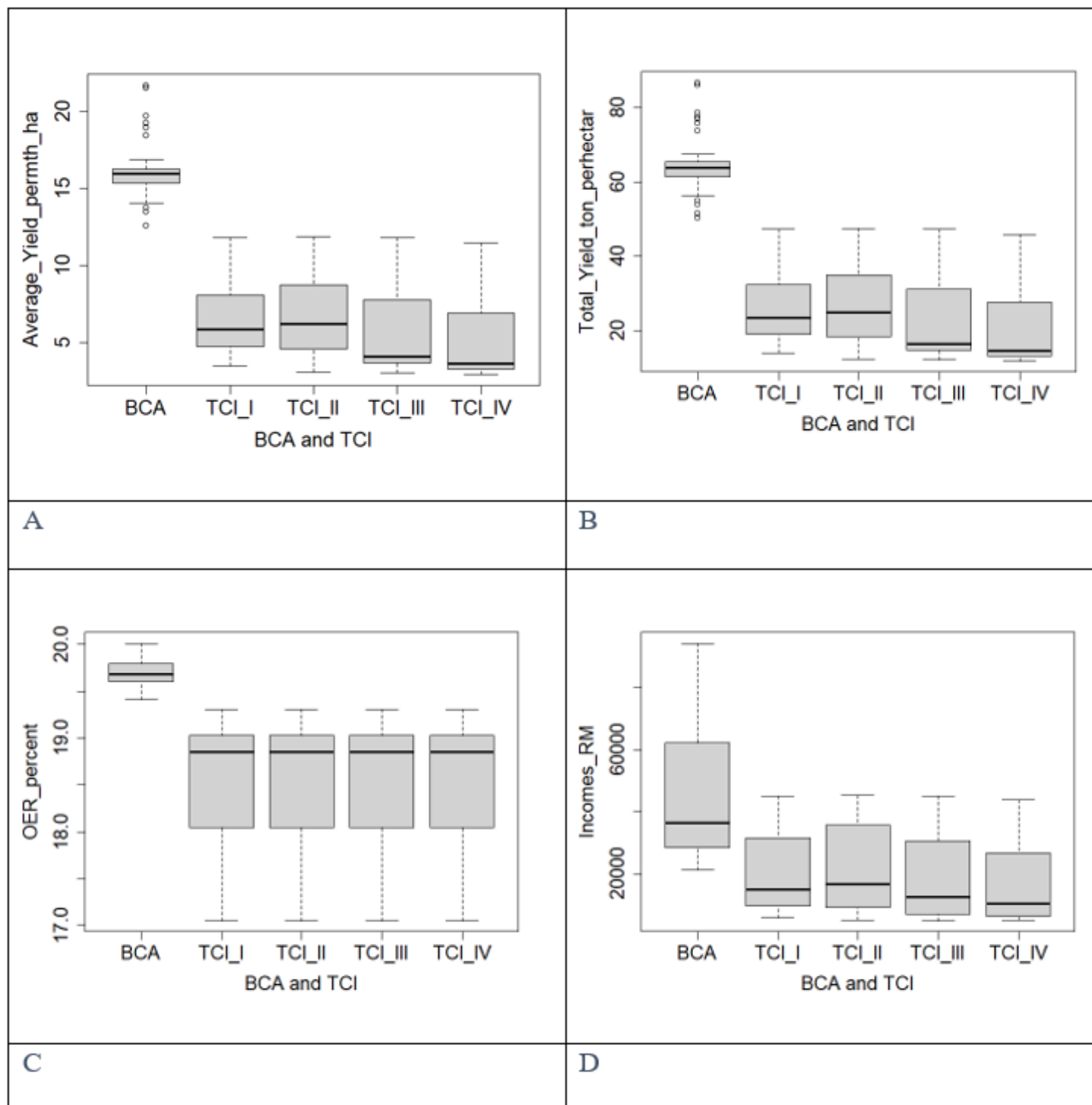


Figure 2

A-D. Graphics summary of the median performance in average yield (A), total yield (B), OER (C), and income (D).

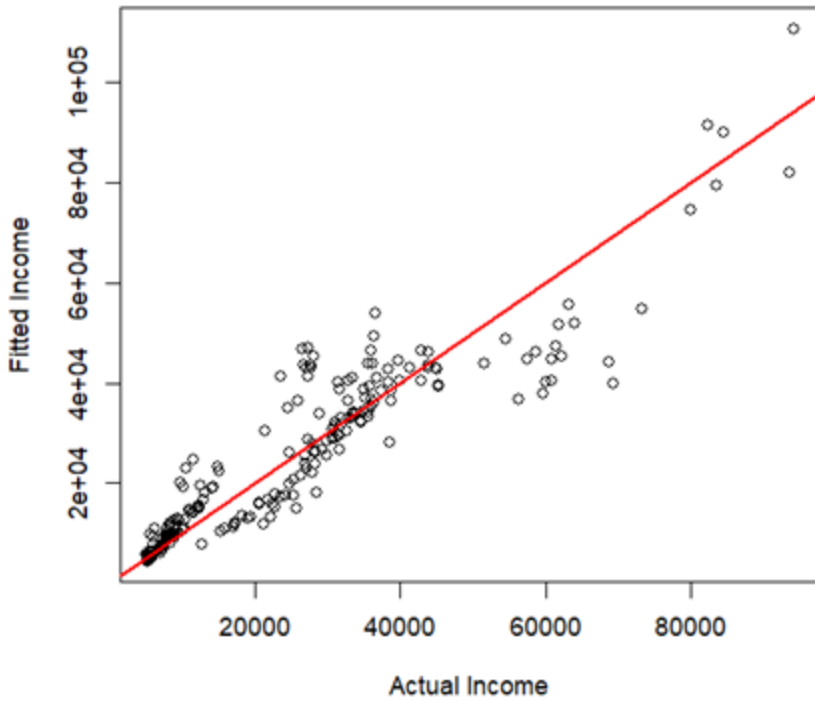


Figure 3

Graphs of the models generated by the generalized additive model (GAM).

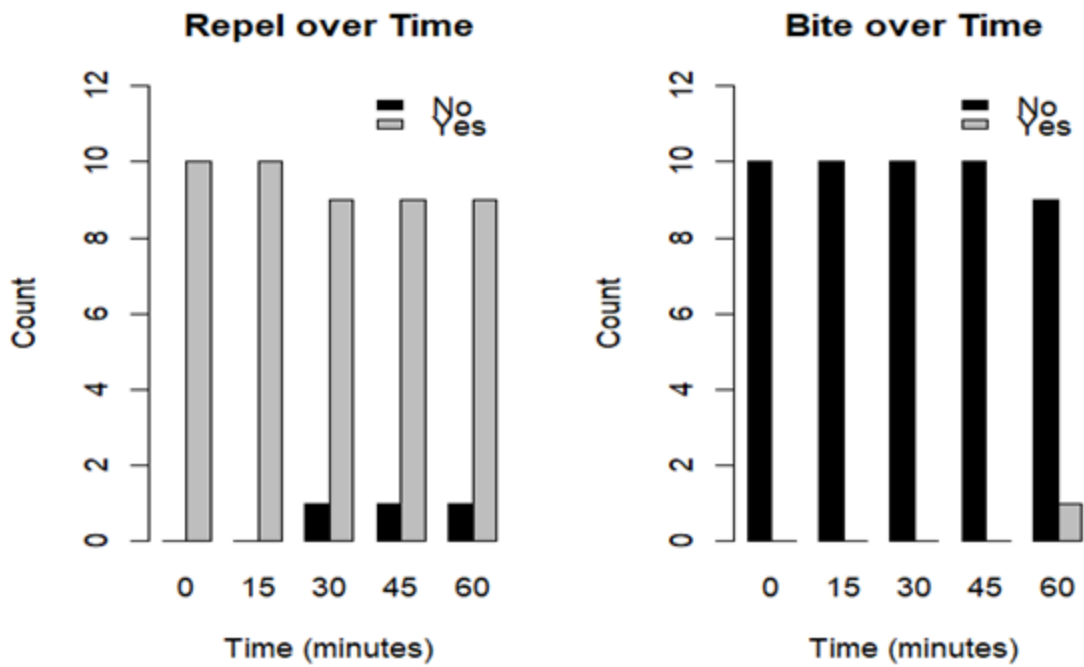


Figure 4

Tea tree essential oil repellency, bite nuisance protection test

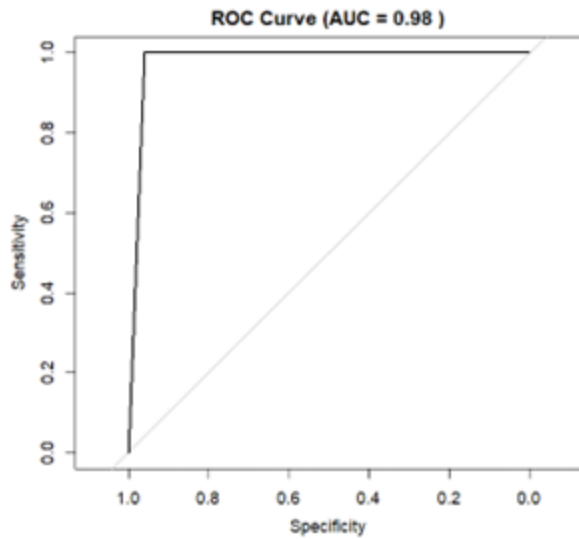


Figure 5

Receiver Operating Characteristic graphic.

Supplementary Files

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- [SupplementaryEMPBCATCI120725.docx](#)