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ORIGINAL RESEARCH ARTICLE

Ecological population dynamics, host preferences, and associated parasitoids of *Bactrocera carambolae* and *Bactrocera papayae* on fruits

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ABSTRACT

BACKGROUND AND OBJECTIVES: Fruit flies are a significant pest affecting fruit production in Indonesia. Understanding the species of fruit flies in fruit-growing regions is crucial for evaluating pest risk, establishing effective plant quarantine measures, and managing control programs. This study aimed to analyze the population dynamics and host preferences of *Bactrocera carambolae* and *Bactrocera papayae* on multiple fruit plants, in addition to exploring the parasitoids associated with these two species of fruit flies.
METHODS: The study was conducted using a survey method in Bogor, Depok, and Indramayu Regency fruit gardens by installing methyl eugenol traps. Randomly selected infected fruits were collected and brought to the laboratory in cages, where they were kept until the emergence of the fruit flies.
FINDINGS: The results show that *Bactrocera carambolae* was more abundant than Bactrocera papayae captured in methyl eugenol-baited traps, particularly during the rainy season. *Bactrocera carambolae* favored star fruit as a host (907.79 flies/trap/month), while Bactrocera papaya preferred papaya (208.46 flies/trap/month), highlighting their distinct oviposition behaviors. The average catches indicated that *Bactrocera carambolae* thrived in moist conditions, while *Bactrocera papayae* flourished in warmer temperatures. Four parasitoid species were identified, including Diachasmimorpha longicaudata and Fopius arisanus, with parasitization rates of 20.40 percent and 12.70 percent, respectively. The findings underscore the potential for effective biological control of the targeted pest species. They indicate that seasonal variations in the availability of host fruits and climatic conditions play a significant role in influencing fruit fly populations and their relationships with parasitoids.
CONCLUSION: This study emphasizes the population dynamics and host plant preferences of *Bactrocera carambolae* and *Bactrocera papayae* in West Java, Indonesia. Four parasitoid species were identified, with Diachasmimorpha longicaudata and Fopius arisanus showing high parasitism rates, suggesting their potential to control fruit fly populations. This study underscores the significance of climate conditions and host availability in creating sustainable and effective pest management approaches for the fruit industries in Indonesia.

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54	9	3

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INTRODUCTION

The agricultural sector plays a crucial role in Indonesia's development, particularly in managing and utilizing strategic resources and food commodities. Within its diverse sub-sectors, horticulture is notable for its substantial potential and its role in enhancing farmers' welfare, driving regional and national economic growth, and generating foreign exchange through export activities. In 2022, the horticulture sector accounted for 1.44 percent (%) of Indonesia's gross domestic product (GDP) (CSAI, 2024a). In 2023, the value of fruit exports will increase by 9.8% compared to 2022. In 2023, the expected revenue from fruit exports is anticipated to reach 460 thousand United States Dollars (USD) (CSAI, 2024b). West Java Province is one of Indonesia's major fruit-producing regions. Several horticultural commodities widely cultivated in West Java and other parts of Indonesia include mango (*Mangifera indica*), star fruit (*Averrhoa carambola*), guava (*Psidium guajava*), Malay apple (*Syzygium malaccense*), and water apple (*Syzygium aqueum*). Rich in vitamins, these fruits are often utilized in beverage formulations and provide various health benefits, including the ability to lower blood pressure and satisfy nutritional demands (Haryono *et al.,* 2016; Yuliadhi *et al.,* 2022; Setiawan *et al.,* 2024). Due to their high economic value, fruit production has steadily increased. In 2023, mango, star fruit, guava, Malay apple, and water apple contributed significantly to the total fruit production in West Java, accounting for 13.6%, 11.6%, 7.3%, 16.9%, and 14.24%, respectively (CSAI, 2024 b). A key factor hindering fruit production is the risk posed by fruit fly infestations. These insects are notable pests of fruit crops and are regarded as primary plant pest organisms. These pests are categorized as quarantine threats, posing significant challenges to the global fruit trade. Infestations found in exported fruits may result in rejection by importing countries, thereby hindering agribusiness operations (Fitrah *et al.,* 2021; Susanto *et al.,* 2022). Fruit flies cause both quantitative and qualitative losses. Quantitative losses arise from diminished harvestable yields, whereas qualitative losses impact the quality of the fruit, especially when secondary bacterial infections lead to fruit decay. Additionally, fruit fly larvae damage the fruit flesh, leading to premature decay and fruit drop before reaching maturity (Danjuma *et al.,* 2014; Muryati *et al.,* 2017). A comprehensive survey has identified 29 different species of fruit flies present throughout the islands of Indonesia (Hidayat *et al.,* 2023). Ardiyanti et al. (2019) reported the presence of 18 fruit fly species in the Bogor area and its surroundings. *Bactrocera* spp. (Diptera: Tephritidae) are among the most significant pests of horticultural crops worldwide, with more than a hundred horticultural plant species serving as potential hosts. In high population densities, infestation intensity can reach up to 100%. Several *Bactrocera* species, including *Bactrocera dorsalis, Fopius arisanus, Bactrocera papayae,* and *Bactrocera philippinensis*, pose serious threats to international agriculture and trade (Ardiyanti *et al.,* 2019; Hidayat *et al.,* 2023; Setiawan *et al.,* 2024). The species *B. carambolae* and *B. papayae* are major concerns for tropical fruit production in Indonesia, leading to considerable repercussions for local and export markets. Infested fruit can lead to trade restrictions and rejections from importing countries (Haryono *et al.,* 2016; Sudiarta *et al.,* 2020; Putri *et al.,* 2024). Consistently recognized as key pests, these two species pose a serious threat to numerous fruits and vegetables in Indonesia, emphasizing the pressing requirement for efficient pest control strategies (Danjuma *et al.,* 2014; Susanto *et al.,* 2022; Putri *et al.,* 2024). Various technologies have been developed for fruit fly control, including fruit bagging, releasing sterile male insects, traps with methyl eugenol, and applying chemical pesticides (Danjuma *et al.,* 2014; Theron et al., 2017; Setiawan *et al.,* 2024). Utilizing natural predators like parasitoid wasps has surfaced as an effective strategy in the realm of sustainable pest management (Vargas *et al.,* 2013; Miranda *et al.,* 2015). Biological control is particularly advantageous as it eliminates chemical residues in fruits, enhances environmental safety, and reduces the risk of pollution (Hudiwaku *et al.,* 2021; Dias *et al.,* 2022). The larval parasitoid from the Braconidae family may serve as a natural enemy to fruit flies (Vargas *et al.,* 2013; Miranda *et al.,* 2015). The Braconidae family, the second-largest family after Ichneumonidae within the Hymenoptera order, primarily consists of parasitoid members (Ovruski *et al.,* 2009). These parasitoids demonstrate a wide host range, preying on a variety of insect pests, including lepidopteran larvae, scale insects, and fruit fly larvae (Vargas *et al.,* 2013; Miranda *et al.,* 2015). Indonesia has documented instances of various parasitoids from the Braconidae family engaging

fruit flies, notably *Fopius arisanus*, *Diachasmimorpha longicaudata*, *F. vandenboschi*, *Opius* sp., and *Biosteres* sp. (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019). Of particular interest, *D. longicaudata* and *F. arisanus* have emerged as promising agents in Indonesia's biological control of fruit fly populations (Haryono *et al.,* 2016; Hudiwaku *et al.,* 2021). To develop successful strategies for managing fruit flies, it is crucial to have an in-depth understanding of the pest species involved (Dias *et al.,* 2022; Yuliadhi *et al.,* 2022; Dominiak and Follett, 2024). The understanding of *B. carambolae* and *B. papayae* species, particularly their population dynamics, host preferences, and associated parasitoids, remains limited. The objective of this study is to investigate the population dynamics and host selection of *Bactrocera carambolae* and *Bactrocera papayae* on multiple fruit plants, in addition to exploring the parasitoids associated with these two two fruit fly species. This study was carried out at Indonesian Center for Agricultural Biotechnology and Genetic Resources Instrument Standard Testing, Bogor, West Java, Indonesia, in 2021.

MATERIALS AND METHODS

Location and sampling sites studied

The research is divided into two parts: field exploration and laboratory experiments. The field research was conducted in the fruit orchard area of Mekarsari Fruit Garden, Cileungsi District, Bogor Regency (S 06°22'401' E 106°58.951'), farmer orchards in Pancoran Mas District, Depok (S 06°22'293', E 106°53'924'), and farmer orchards in Krasak Village, Jatibarang District, Indramayu Regency (S 06°27'40.42" S, E 108°17'55.29"), West Java Province, Indonesia (Fig. 1). In West Java Province, these three areas are vital production hubs for star fruit, mango, guava, papaya, and water apple, overseen by small and medium-scale farmers and entrepreneurs. The study took place at the Entomology Laboratory within the Indonesian Center for Agricultural Biotechnology and Genetic Resources Instrument Standard Testing, Bogor. This research focused on two species of fruit flies, *Bactrocera carambolae* and *Bactrocera papayae*. In Indonesia, these pests represent a serious challenge, leading to substantial economic losses in the cultivation of fruits and vegetables. The polyphagous insect of these two fruit fly species poses a serious threat to commercial crops, including vegetables and fruits such as mango, star fruit, water apple, guava, malay apple, papaya, melon, breadfruit, jackfruit, tomato, and chili. Field exploration was conducted to assess the population dynamics of fruit flies in traps and infested fruits, as

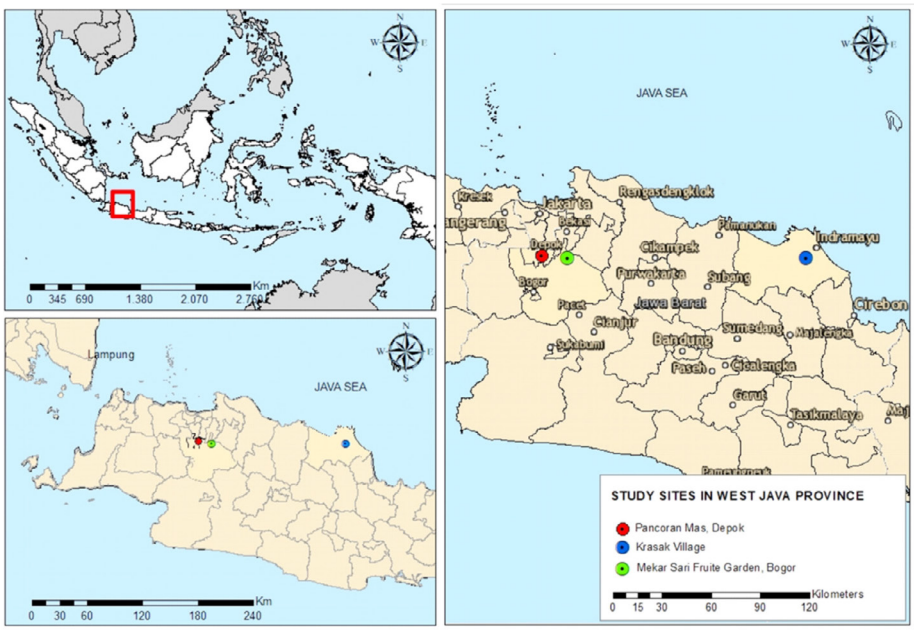

Fig. 1: Geographical location of the study area in west Java Province, of Indonesia indicated with green, red, and yellow circles indicating the trapping locations of fruit flies

well as their associated parasitoids. Meanwhile, the laboratory research aimed to evaluate the preference and performance of fruit flies on several host plants. The host plants used in this research consisted of five types: star fruit (*Averrhoa carambola*), mango (*Mangifera indica*), guava (*Psidium guajava*), water apple (*Syzygium aqueum*), and papaya (*Carica papaya*).

Population dynamics of fruit flies

The population dynamics of *B. carambolae* and *B. papayae* fruit flies were monitored using two methods: installing attractant traps containing methyl eugenol and collecting infested fruits. This section of the study yielded important findings regarding the population dynamics of fruit flies in relation to various host plants and the fruits impacted by infestations in agricultural areas focused on fruit production.

Fruit flies in traps

The traps used in this study were Steiner traps modified from Hasyim *et al.* (2008). These traps made from plastic bottles, each 30 centimeters (cm) in length and 8 cm in diameter. A pair of holes, each 1 cm in diameter, was drilled on opposite sides of the bottle, permitting the insertion of a tube for fruit fly access. A wire was attached to the bottle's cap to suspend the tube, which was 0.3 cm in diameter and 2 cm in length, containing methyl eugenol-soaked cotton, which was positioned in the upper third of the bottle. At the bottom, 4 cm of liquid detergent diluted with water was added as a killing agent for captured fruit flies. The traps were installed on five host plants: star fruit, mango, guava, water apple, and papaya. They were placed 1,5 meters above ground level beneath the tree canopy (Hasyim *et al.,* 2006). Four traps were installed in each location, covering an area of approximately 5000 square meters (m^2), spaced 20 meters apart. The observation period spanned 12 months, with sessions held at three-day intervals. The total number of fruit fly species captured in all traps was recorded and identified based on Siwi *et al.* (2006).

Fruit flies within fruits infested

Infested fruits were collected from star fruit, mango, guava, water apple, and papaya. Over the course of the study, collections were performed 12 times at two-week intervals, with ten fruit samples from each species collected during each session. They were kept at 28 degrees Celsius (°C) and 70% relative humidity. The fruits were stored in plastic jars measuring 6 cm in diameter and 20 cm in height with nylon mesh covering the top. After a 14-day incubation, the fruit was peeled to obtain the pupae of the fruit flies. Each pupa was transferred to a plastic box measuring 10 cm × 10 cm × 5 cm, with the bottom lined with sterile sawdust. The development of the pupae was monitored on a daily basis until the adult fruit flies emerged, after which the species were identified and the number of individuals was counted.

Mass rearing of fruit flies

Fruit flies were obtained from infested fruits collected from the Mekarsari Fruit Garden. Identification of the fruit flies was conducted to select the appropriate species for the study, namely *B. carambolae* and *B. papayae*. The mass rearing of both species was carried out in the laboratory under temperature of 28 °C, humidity of 70%, and 12 hours (h) lighting. The infested fruits were kept in cages measuring 50 cm × 50 cm × 25 cm, with a six cm-thick layer of sawdust at the base to serve as a pupation site. Weekly sifting of the sawdust was conducted to extract and collect the pupae that had formed. All collected pupae were stored in petri dishes and placed in cages measuring 40 cm × 40 cm × 40 cm. Inside these cages, adult fruit flies were provided with food consisting of sponges soaked in water, petri dishes containing a mixture of protein hydrolysate and granulated sugar (1:4, weight per weight (w/w)), and honey solution (10%) soaked in cotton (Vargas *et al.,* 2000; Hasyim *et al.,* 2008). Following a ten-day interval, eggs were harvested with a tube that measured 1.5 cm in diameter and 15 cm in height, and they were preserved until they reached the pupal stage. Pupae that had formed within the sawdust were collected by passing the material through a 60-mesh screen, and the adult fruit flies that emerged were subsequently returned to cages for further cultivation.

Host preference of B. carambolae and B. papayae on different fruits

Five hundred pairs of male and female *B. carambolae* and *B. papayae* were placed separately in cages measuring 50 cm × 50 cm × 50 cm, with methyl eugenol applied to stimulate copulation.

After copulation, 100 females were replaced with plastic containers measuring 30 cm in height and 30 cm in diameter connected to five smaller containers measuring 17 cm in height and 16 cm in diameter. Host fruit designated for oviposition was placed in each of the smaller containers. An exhaust fan was installed at the upper section of the fruit fly enclosure to direct the scent of the fruit into the containers, facilitating the entry of fruit flies into the container that corresponded to their preferred host fruit. Fruit fly infestation on the host fruits was recorded over 48 h, after which all females were removed from the plastic containers. Utilizing jars to confine fruit flies in order to study host preference may not completely mimic their natural conditions, which points to a limitation within this study. The experiment was conducted using a completely randomized design with five treatments (star fruit, papaya, guava, water apple, and papaya) and four replications. The host preference tests for *B. carambolae* and *B. papayae* were conducted separately for each species at different times. The study monitored several parameters, including the number of fruit flies that approached the host fruit, the total oviposition punctures made, the number of eggs laid, the count of pupae, the duration of the pupal phase, the number of adult fruit flies that emerged, the emergence rate of pupae into adults, and the sex ratio of the adults.

Fruit fly parasitoids

The observation of parasitoids was carried out by collecting infested fruits. The study focused on star fruit, mango, and guava, with a total sample of 50 infested fruits collected from each host species. All harvested fruits were stored in plastic containers, each measuring 20 cm in height and 15 cm in diameter, with a layer of sterilized sawdust at the bottom to facilitate pupation. The infested fruits were incubated for 14 days before being peeled to extract the fruit fly pupae until 100 pupae for each host fruit. Each pupa was replaced with a plastic container measuring 10 cm × 10 cm × 5 cm, with sterilized sawdust lining the bottom. The development of pupae was monitored on a daily basis to identify the emergence of either fruit flies or parasitoids. Parasitoids were identified using the identification keys by Goulet and Huber (1993) and Shaw and Huddleston (1991).

Data analysis

The data on the population dynamics of fruit flies were analyzed using analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test at a 5% significance level. Data on abiotic factors such as temperature, rainfall, and rainy days were sourced from climate stations in Bogor, Indramayu, and Depok, West Java Province, and subsequently averaged on a monthly basis. Further examination of the data was carried out utilizing Pearson correlation and generalized linear model (GLM) regression analysis. The analyses were executed withR version 4.1.1.

RESULTS AND DISCUSSION

Fruit flies caught in traps

Two species of adult male fruit flies were captured in methyl eugenol-baited traps during the study. Based on morphological characteristics, the two fruit flies were identified as *Bactrocera carambolae* Drew and Hancock and *Bactrocera papayae* Drew and Hancock. The main morphological feature of *B. carambolae* is the overlapping of the costal band of the wing with vein R_{2+3}. The abdomen displays a T-shaped arrangement featuring a prominent dark band that runs longitudinally in the center, while the anterolateral corner of the fourth tergite is shaped like a square (Fig. 2B). In contrast, the main morphological feature of *B. papayae* is that the costal band of the wing runs parallel to or crosses R_{2+3}. The abdomen presents a T-shaped design featuring a narrowed dark band along the medial longitudinal axis, with the anterolateral corner of the fourth tergite appearing either triangular or not present at all (Fig. 3B). Both species of fruit flies are polyphagous pests with a wide host range, including star fruit, jackfruit, mango, papaya, citrus, water apple, guava, malay apple, soursop, sugar apple, avocado, chili peppers, cayenne pepper breadfruit, cempedak, and rambutan. The current study did not perform molecular analyses on the two fruit fly species, *B. carambolae* and *B. papayae*. Nevertheless, there is a wealth of research that has examined the genetic variations that exist between these species. Studies employing microsatellite markers have shown that there are notable genetic differences in B. carambolae populations depending on their geographic regions (Schutze *et al.,* 2014; Aketarawong *et al.,* 2015). These variations influence their adaptability and infestation patterns. *B. papayae* is more invasive, having successfully spread across Southeast Asia due to its

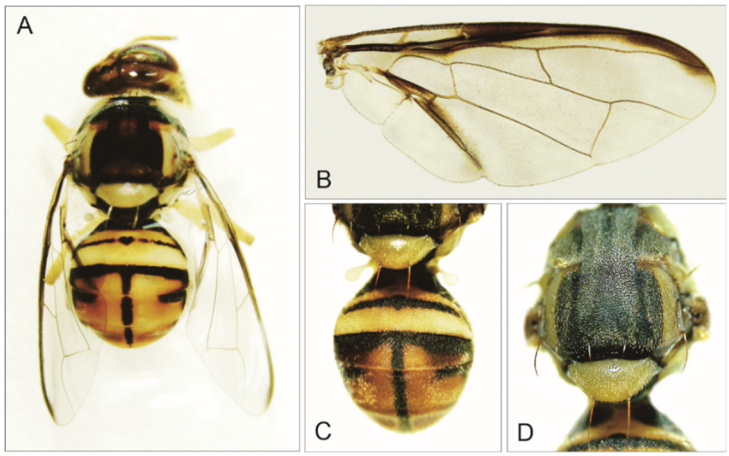

Fig. 2: *Bactrocera carambolae* male. A) dorsal view, B) wing, C) abdomen, D) scutum

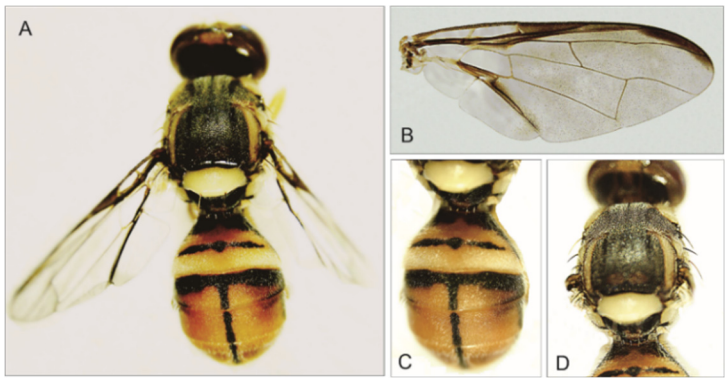

Fig. 3: *Bactrocera papayae* male. A) dorsal view, B) wing, C) abdomen, D) scutum

greater genetic diversity and adaptability to various host plants and climates (Qin *et al.,* 2018; Jaffar *et al.,* 2023). In contrast, *B. carambolae* remains largely confined to the northern regions of South America, where it primarily infests *Averrhoa carambola* (Deus *et al.,* 2024).

The population of both fruit fly species varied each month among the orchards. *B. carambolae* was captured significantly more than *B. papayae* across all observed fruit types and was most abundant during the rainy season. The presence of fruit flies in the traps was notably impacted by variations in rainfall and temperature (Fig. 4). The results of this study demonstrate that methyl eugenol is effective for monitoring male populations of *B. carambolae* and *B. papayae*. Adult *B. carambolae* catches were generally higher in February, March, October, November, and December, coinciding with increased rainfall (Fig. 4A). Conversely, the capture rates of male B*. papayae* appeared to increase with higher maximum temperatures and a reduction in rainfall (Fig. 4B). Indonesia is an equatorial country with a tropical climate characterized by warm temperatures and high humidity throughout the year. Indonesia experiences two seasons: the rainy season, which lasts from October to March, and the dry season, which typically occurs from April to September. Table 1 illustrates the correlation between the abundance of fruit flies and various weather parameters. Rainfall indicated a positive and significant correlation with the abundance of *B. carambolae*, whereas temperature did not show a significant correlation. In contrast, there was a positive correlation between maximum temperature and the abundance of *B.*

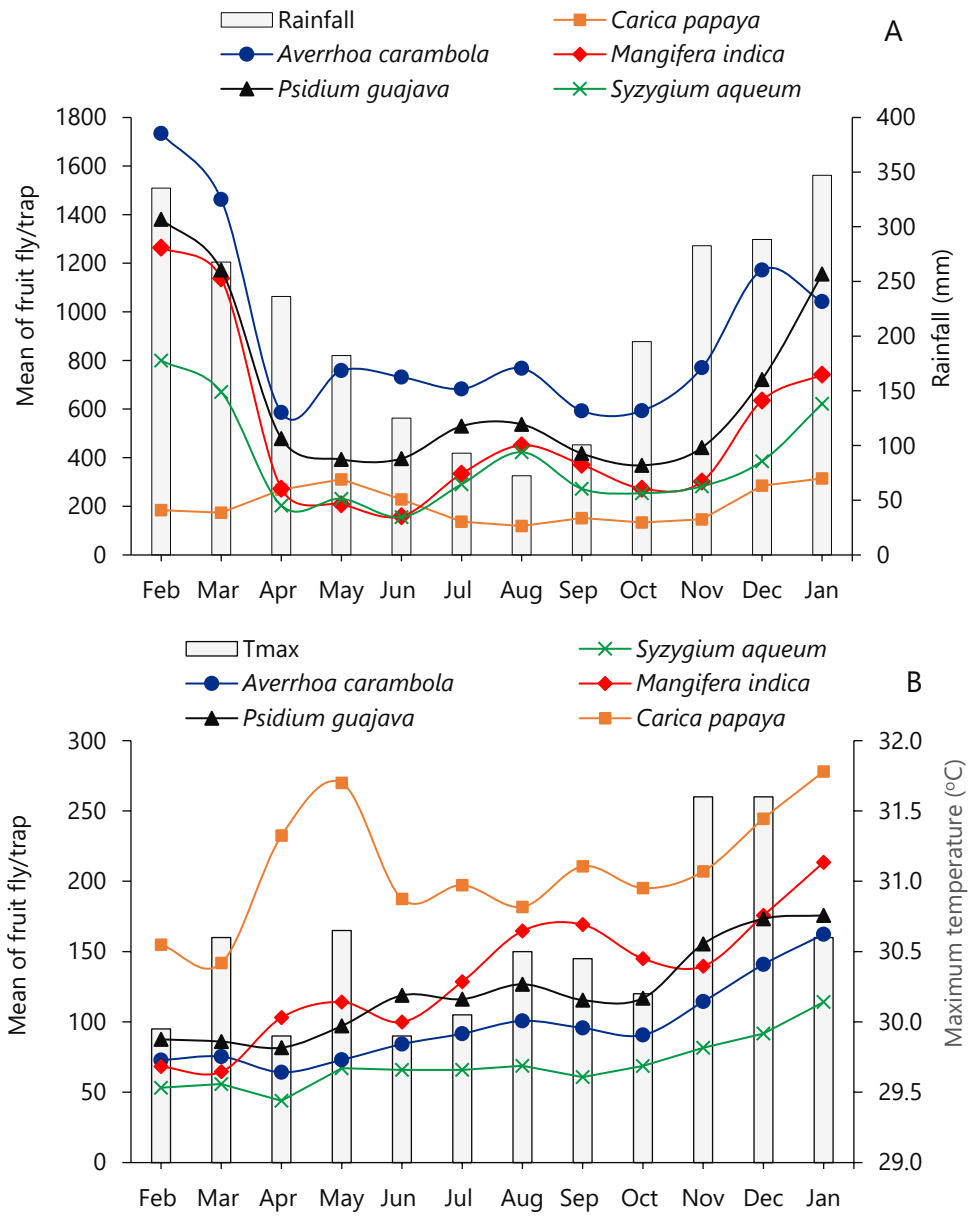

Fig. 4: Population dynamics of male fruit flies collected per trap per month in relation to rainfall and *B. carambolae* (A), and maximum temperature and *B. papayae* (B) in orchards of star fruit, mango, guava, water apple, and papaya

papayae on host plants, excluding mango, while rainfall did not reveal any significant correlation. Generally, weather factors, temperature, and rainfall were essential variables influencing the distribution of fruit flies. The variations in climate noted in this study imply potential consequences related to climate change. It is projected that climate change will impact fruit fly populations by extending their distribution, changing their life cycles, and increasing the likelihood of infestations. Rising temperatures and changing precipitation patterns may facilitate the spread of invasive species into new regions.

Table 1: Relations between weather parameters and male fruit flies caught per trap per month in orchards of star fruit, mango, guava, water apple, and papaya

Host plant	Pearson correlation coefficient (r)				Multiple linear regression equation (Y)	R^2
	X_1	X_2	X_3	X_4		
B. carambolae						
A.carambola	0.101	0.408	-0.022	0.628*	$Y= 5372 - 339 X_1 - 333 X_2 + 457 X_3 + 5.37 X_4$	51.81
M. indica	0.019	0.375	-0.135	0.588*	$Y= 8865 - 360 X_1 - 321 X_2 + 317 X_3 + 5.04 X_4$	46.95
P.guajava	-0.035	0.487	-0.239	0.671*	$Y= 10300 - 321 X_1 - 215 X_2 + 137 X_3 + 4.48 X_4$	56.00
C. papaya	0.130	0.481	0.388	0.681*	$Y= -3636 + 39.3 X_1 + 74.7 X_2 + 49.7 X_3 - 0.16 X_4$	61.99
S. aqueum	0.017	0.313	-0.281	0.575*	$Y= 7147 - 188 X_1 - 179 X_2 + 76 X_3 + 2.71 X_4$	46.76
B. papayae						
A.carambola	0.599*	-0.072	-0.301	0.308	$Y= -294 + 42.4 X_1 + 13.2 X_2 - 46.4 X_3 - 0.10 X_4$	53.96
M. indica	0.425	-0.272	-0.198	-0.072	$Y= -587 + 66.6 X_1 + 29.9 X_2 - 73.9 X_3 - 0.38 X_4$	43.86
P.guajava	0.676*	-0.215	-0.264	0.203	$Y= -422 + 51.0 X_1 + 11.2 X_2 - 49.1 X_3 - 0.13 X_4$	61.68
C. papaya	0.511*	0.302	0.211	0.179	$Y= -2135 + 65.5 X_1 + 63.5 X_2 - 32.3 X_3 - 0.45 X_4$	52.28
S. aqueum	0.573*	-0.006	-0.320	0.317	$Y= -257 + 31.2 X_1 + 14.9 X_2 - 36.3 X_3 - 0.11 X_4$	57.49

X_1 = maximum temperature; X_2= minimum temperature; X_3= average temperature, X_4= rainfall (mm); Y = number of fruit flies; * Significant at P≤0.05.

Evidence suggests that the ideal habitats for fruit flies are evolving, emphasizing the importance of implementing updated monitoring and management strategies. Furthermore, variations in temperature can influence the development and reproduction of fruit flies, thereby impacting their population dynamics (Jaffar *et al*., 2023; Kolopaking *et al.,* 2023). These findings emphasize the importance of adaptive pest control strategies to mitigate climate-related threats.

The present study revealed that the average abundance of male *B. carambolae* captured was highest on star fruit (907.79 flies/trap/month), followed by guava (666.23 flies/trap/month), mango (512.67 flies/trap/month), water apple (382.67 flies/trap/month), and papaya (204.41 flies/trap/month). The capture rate of male *B. carambolae* on star fruit was found to be statistically significantly greater, with the exception of comparisons made with guava (Fig. 5). Furthermore, male *B. papayae* were most frequently captured on papaya (208.46 flies/trap/month), with a statistically significant difference compared to mango (132.20 flies/trap/month), guava (120.97 flies/trap/month), star fruit (97.17 flies/trap/month), and water apple (69.75 flies/trap/month).

The current study reveals that *Bactrocera carambolae* and *Bactrocera papayae* were the two main species of fruit flies affecting fruit cultivation in Indonesia, particularly in West Java Province. Both species are polyphagous, capable of infesting over 300 host plants across 40 families (Amin *et al.,* 2019). The prevalence of fruit flies is influenced by factors such as geographic location, seasonal variations, the presence of specific host plants, and the fruiting period of host plants (Danjuma *et al.,* 2014; Amin *et al.,* 2019; Hudiwaku *et al.,* 2021). The success of pupation and emergence rates for *B. carambolae* and *B. papayae* are greatly affected by site conditions, including soil composition and the characteristics of microhabitats (Susanto *et al.,* 2022; Lin and Okuyama, 2024). Soil texture, moisture content, potential of hydrogen (pH), and pupation depth significanly influence the pupation success and emergence rates of these fruit flies. Sufficient soil moisture is essential for successful pupation. While there is limited research focused specifically on *B. carambolae* and *B. papayae*, studies on related species indicate that both excessively dry and overly moist soil conditions can adversely affect the survival and emergence of pupae (Susanto *et al.,* 2022; Lin and Okuyama, 2024). The present study indicates that *B. carambolae* was present in significantly higher abundance than *B. papayae*, with peak populations occurring during the rainy season. These findings align with Setiawan *et al*. (2024), who monitored fruit fly composition on several host plants (apple, large chili, red guava, sweet citrus, and tomato) and found that *B. carambolae* ranked first, while *B. papayae* ranked third in terms of captured fly populations. Likewise, Putri *et al*. (2024) conducted an assessment of fruit fly populations through the use of pheromone traps, revealing that male *B. carambolae* were more prevalent than other fruit fly species. They also reported that fruit fly populations peaked in October and March but declined until April and

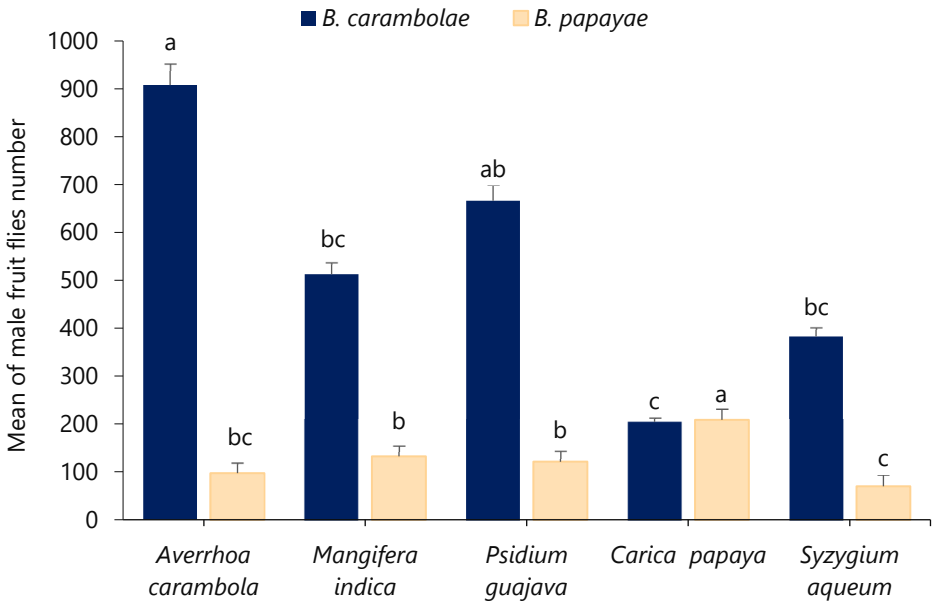

Fig. 5: The mean number of *B. carambolae* and *B. papayae* male caught per trap during a year in star fruit, mango, guava, water apple, and papaya orchards. Values are mean ± standard error (SE). The means with the same letters for each variable were not significantly different (Tukey's HSD, $P < 0.05$)

September. A combination of environmental factors and intrinsic characteristics of the species and individuals influences the dynamics of fruit fly populations. This study found a significant association between the number of trapped fruit flies and environmental conditions, particularly temperature and rainfall. It was indicated that increased temperature and rainfall enhance the number of fruit flies captured in traps. The study shows that rainfall, temperature, and host plant species are the primary environmental factors affecting the population fluctuations of *B. carambolae* and *B. papayae*. The dynamics of fruit fly populations in tropical regions are shaped by various essential elements, including the availability of host and non-host plants, along with temperature and precipitation levels (Danjuma *et al.,* 2014; Pogue *et al.,* 2024). The population of fruit flies directly influences the population of other insects, particularly their parasitoids. A rise in the population of fruit flies is associated with an increase in the number of parasitoids, whereas a reduction in fruit flies corresponds to a decrease in parasitoid numbers (Ardiyanti *et al.,* 2019; Susila and Supartha, 2020). Overall, the temperature conditions in West Java Province were suitable for the population development of *B. carambolae* and *B. papayae*, which explains why these fruit flies are present throughout the year. The air temperature during the dry season tends to be higher, falling within the optimal range for *B. papayae*, which favors an increase in its population. Additional findings suggest that sustained elevated temperatures benefit the population development of *B. papayae*. The monthly maximum temperatures at the study locations ranged from 29.90 °C to 31.60 °C, representing ideal conditions for insect development year-round. emperature is a key factor affecting the growth and survival of *B. papayae*, which demonstrates a greater adaptability to higher temperatures than *B. carambolae*. In general, *B. papayae* prospers in regions where the temperature is between 25 °C and 30 °C (Danjuma *et al.,* 2014; Amin *et al.,* 2019; Pogue *et al.,* 2024). Conversely, the high rainfall during the study period was beneficial for the population development of *B. carambolae*. The location where *B. carambolae* was discovered experienced an extended rainy season and recorded the highest density throughout this study. Weather data collected during the study revealed a distinct difference between the dry and

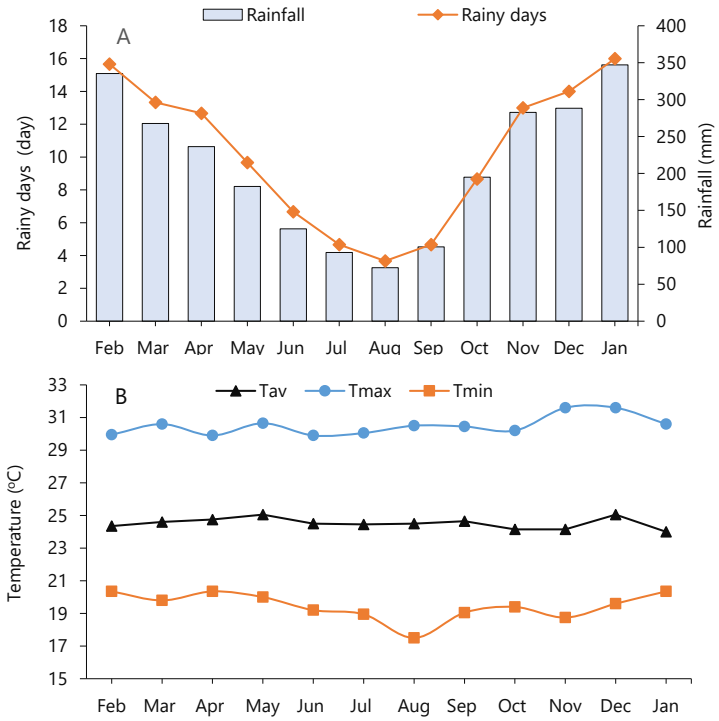

Fig. 6: Weather conditions at the research sites. Rainfall with rainy days (A) and monthly temperature (Tav: average temperature, Tmax: maximum temperature, Tmin: minimum temperature). The rainy season corresponds from October to March, while the dry season corresponds from April to September 2021

rainy seasons in terms of rainfall but not in temperature, with more significant precipitation occurring during the rainy season (Fig. 6). Susanto *et al.* (2017) and Putri *et al.* (2024) captured more fruit flies in traps during periods of rainfall between 160 and 200 millimeters (mm) (comparable to the rainfall levels in this study). Generally, fruit fly populations increase with rising rainfall (Hasyim *et al.*, 2008; Putri *et al.*, 2024). The survival, reproductive rates, and movement patterns of adult flies are directly influenced by rainfall, which also has an indirect effect on the availability of host fruits and the presence of natural enemies (Amin *et al.*, 2019). Increased rainfall can trigger the emergence of new adults; however, excessive rain can lead to pupal mortality and hinder the daily activity of fruit flies (Dominiak and Follett, 2024; Soares *et al.*, 2023). Furthermore, increased rainfall impacts the synchronization of growth and development in host plants (Hasyim *et al.*, 2008; Amin *et al.*, 2019). The interplay between rainfall and host plants is marked by the timing of fruit production and the robust vegetative growth of the host plants, both of which can impact the local fruit fly population (Soares *et al.*, 2023; Dominiak and Follett, 2024). A higher availability of host plants and fruits can influence the number of fruit fly populations. The greater the availability of hosts and fruits, the more likely the fruit fly populations will increase in the area (Hidayat *et al.*, 2023; Setiawan *et al.*, 2024). Environmental factors significantly impact the seasonal population dynamics of *B. carambolae* and *B. papayae*, influencing their reproductive cycles, infestation patterns, and survival rates (Amin *et al.*, 2019; Susanto *et al.*, 2022). The populations of seasonal fruit flies are heavily influenced by environmental conditions, particularly temperature and rainfall. These abiotic factors influence key aspects of fruit fly biology, including reproduction, development, and survival rates. *B. dorsalis* populations tend to increase with rising temperatures, as higher temperatures accelerate development and boost reproductive rates, often leading to population surges. The dynamics of fruit fly populations are also notably

impacted by rainfall. An increase in precipitation leads to better survival and reproductive outcomes, with studies demonstrating a clear positive correlation between rainfall amounts and fruit fly capture rates. It suggests that wetter conditions may support higher fruit fly populations. Besides temperature and rainfall, interspecific competition and ecological interactions play a crucial role in shaping the population structure and adaptability of *Bactrocera carambolae* and *Bactrocera papayae*. These interactions influence their survival, reproductive success, and spatial distribution through mechanisms such as resource competition and competitive displacement (Schutze *et al.,* 2014). Monitoring the capture of fruit flies in traps set up in a particular area provides insights into the population densities of fruit fly species present. Nevertheless, this observation alone does not confirm their interaction with host plants. A study on the habitat use by *B. carambolae* and *Bactrocera dorsalis* in fruit orchards across various geographical regions demonstrated that the flies migrate between microhabitats and other host plants to forage and oviposit, particularly utilizing mangosteen trees for resting and feeding (Kolopaking *et al.,* 2023). The rich diversity of host plant species in varied environments offers an optimal condition for the expansion of fruit fly populations (Hidayat *et al.,* 2023). To mitigate their spread, stringent quarantine measures must be enforced for fruit and vegetable products entering or exiting Indonesia. Moreover, domestic quarantine regulations are crucial to preventing the movement of fruit flies between endemic and non-endemic regions within the country (Larasati *et al.,* 2013; Ariningsih *et al.,* 2022). Furthermore, the type of trapping system and the attractants used for sampling can significantly impact the success of fruit fly capture in traps. More fruit flies are typically captured when traps are placed at the edge of the field rather than within the field (Susanto *et al.,* 2017; Amin *et al.,* 2019; Setiawan *et al.,* 2024). Habitat modification, including deforestation and urbanization, significantly impacts the abundance and distribution of *Bactrocera carambolae* and *Bactrocera papayae*. The alterations in the environment influence the availability of host plants, the conditions of the microclimate, and the interactions within the ecosystem, which collectively determine the dynamics of fruit fly populations. *B. carambolae* prefers humid environments and is more sensitive to deforestation (Raghu *et al.,* 2000). The loss of primary host plants, such as star fruit, leads to population declines in deforested areas. While urbanization often results in diminished host plant diversity, it can simultaneously introduce ornamental and backyard fruit trees, potentially fostering the growth of fruit fly populations.

Fruit flies within fruits infested

Based on the rearing of infested fruits, it was found that star fruit, mango, papaya, guava, and water apple collected from the field were infested by *Bactrocera carambolae* Drew and Hancock and *Bactrocera papayae* Drew and Hancock. Even with the varied landscapes and distant sampling locations, the species of fruit flies that emerged from the infested fruits were identical. In general, the infestation pattern of both fruit fly species tended to increase from the first observation to the twelfth. Interestingly, the number of emerging fruit flies decreased during the ninth observation but rose again from the tenth to the twelfth observations (Fig. 7). This trend is consistent with the quantity of fruit flies collected in field traps (Fig. 4). The number of adult *B. carambolae* emerging from infested fruits was highest in star fruit (39.69 individuals) and lowest in papaya (1.75 individuals). Statistical analysis showed that the number of *B. carambolae* emerging from infested star fruit significantly differed from mango, papaya, and water apple, except for guava. For *B. papayae*, the adult fruit fly population was most abundant in papaya (16.98 individuals) and lowest in water apple (6.48 individuals). The data showed a notable contrast when compared to mango, star fruit, guava, and water apple (Fig. 8). The fruit flies emerging from the infested fruits displayed a pattern akin to that of the fruit fly population found in the traps. High fruit fly populations in the traps were mirrored by high populations emerging from infested fruits.

Consistent with trap capture data, the emergence of *Bactrocera carambolae* and *Bactrocera papayae* from infested fruit was notably higher in star fruit and papaya. It has been noted that the availability of host plants for fruit flies fluctuates based on seasonal factors and the specific species of host plants present. Seasonal fluctuations significantly affect the population dynamics of fruit flies, as evidenced by both trap captures and fruit emergence. The infestations of *B. carambolae* and *B. papayae* align with the fruiting periods of star fruit, mango, guava, water apple, and papaya in West Java Province, coinciding with the rainy season, which exhibits consistent patterns throughout

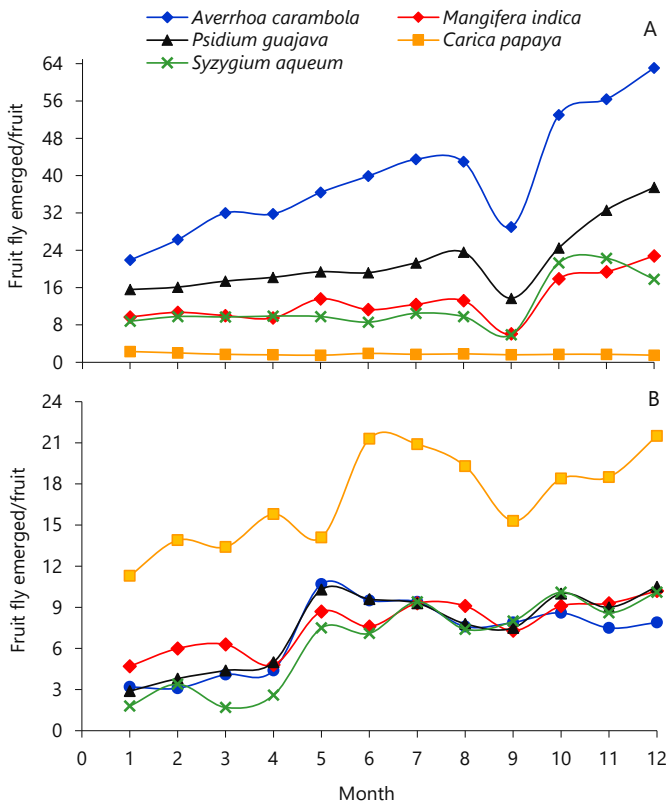

Fig. 7: The seasonal population of adult fruit flies emerged from infested fruit samples of star fruit, mango, guava, water apple, and papaya from fields, caused by *B. carambolae* (a) and *B. papayae* (b).

the months. A significant rise in the populations of *B. carambolae* and *B. papayae* at the beginning of the rainy season results in extensive fruit damage during the mid and late seasons. Infestation rates of *B. carambolae* and *B. papayae* are influenced by both seasonal factors and the availability of host fruits. It was suggests that these two elements independently contribute to the patterns of fruit fly infestations in orchards (Sudiarta *et al.,* 2020; Pogue *et al.,* 2024; Putri *et al.,* 2024). The influence of fruit availability in orchards is nuanced; an increase in the quantity of fruit and variability in ripeness can result in fruit damage from dilution effects, while also facilitating elevated oviposition rates of fruit flies (Muryati *et al.,* 2017; Grechi *et al.,* 2021; Saeed *et al.,* 2022). Economic losses caused by fruit fly infestations vary by region. In Simalungun Regency (North Sumatra, Indonesia), fruit fly damage to orange crops results in losses of 960 United States Dollars per hectare USD /ha) annually. In Indramayu, mango losses amount to 4.42 tons per hectare per year (tons/ ha/y) valued at 4,477 USD/ ha annually. For comparison, fruit fly infestations (*Bactrocera dorsalis*) in mango plantations in Manica Province, Mozambique, cause an average yield loss of approximately 5.65/tons/ha, translating to a financial loss of $US3,428.97/ha (Ariningsih *et al.,* 2022).

Fruit flies preference

The study on the preferences of *B. carambolae* and *B. papayae* for several types of fruit indicates that *B. carambolae* prefers star fruit, while *B. papayae* was more attracted to papaya. It was evidenced by the number of fruit flies that entered the jars containing the fruit and the number of ovipositor punctures. A total of 47.00 individuals of *B. carambolae* chose star fruit, while only 3.75 individuals selected papaya. *B. papayae*, 43.8 individuals chose papaya, with the lowest numbers on star fruit and water apple, each

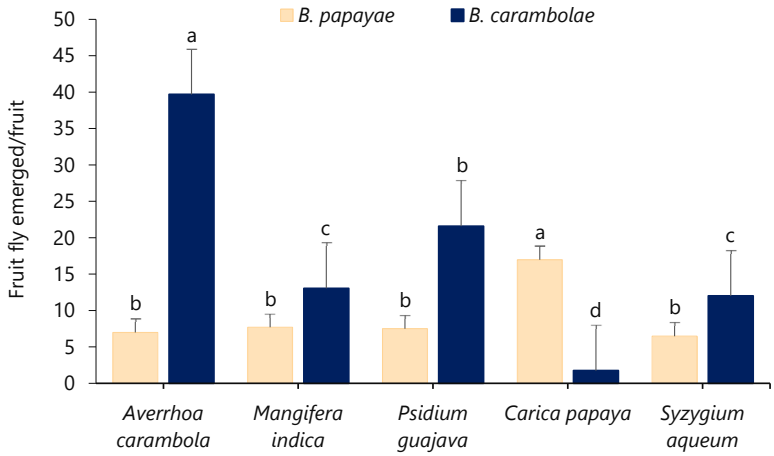

Fig. 8: The mean number of *B. carambolae* and *B. papayae* emerged per fruit sample in infested star fruit, mango, guava, water apple, and papaya orchards. Values are mean ± SE. The means with the same letters for each variable were not significantly different (Tukey's HSD, $P < 0.05$)

of them 6.5. Moreover, the mean count of ovipositor punctures recorded on star fruit was 70, in contrast to the 73 punctures noted on papaya infested with *B. papayae*. Additionally, the highest number of eggs laid by *B. carambolae* was found on star fruit, whereas *B. papayae* laid the most on papaya, with 173.8 and 180.3 eggs, respectively. A correlation was observed between the number of eggs laid and the ovipositor punctures in the fruit; specifically, a higher count of punctures resulted in an increased number of eggs deposited (Fig. 9). As the eggs developed into larvae and pupae, the number of *B. carambolae* pupae were found to be the highest on star fruit and lowest on papaya, with counts of 49.50 and 10.50 pupae, respectively. Interestingly, this pattern was reversed for *B. papayae*. The number of pupae was higher in papaya (42.50 pupae) and lower in star fruit (19.00 pupae) (Table 2). The study also revealed a relationship between the quantity of pupae that emerged and the total number of eggs deposited. As the number of eggs laid increased, so did the number of emerging larvae. The proportion of *B. carambolae* eggs that developed into pupae ranged from 15% to 40%, while for *B. papayae*, it ranged from 21% to 64%.

The percentage of *B. carambolae* adults emerging from pupae was highest on star fruit and lowest on water apple, at 90.40% and 57.37%, respectively, for 7-8 days. Additionally, the percentage of *B. papayae* adults emerging from pupae was highest on papaya (85.95%) and lowest on star fruit (57.90%), with a pupal period of 7-9 days. These findings reveal that each species shows a distinct preference for certain host plants, with the availability of these preferred fruits having a positive correlation with the growth and development of fruit fly populations. Furthermore, among the emerging adults were found that the number of female flies was higher than that of males for both *B. carambolae* and *B. papayae* across all tested host plants. These findings suggest that female fruit flies play a crucial role in sustaining populations in the field. The fruit fly species *Bactrocera carambolae* and *Bactrocera papayae* maintained in jars exhibit different preferences for various host plant species. The results of this study highlight that *B. carambolae* predominantly chooses star fruit, in contrast to *B. papayae*, which exhibits a preference for papaya over alternative fruits. This preference was evidenced by the more significant number of *B. carambolae* entering star fruit and *B. papayae* entering papaya (Fig. 5). Star fruit was identified as the most favored host for oviposition by *B. carambolae*. At the same time, the papaya was the preferred host for *B. papayae*, with the highest number of pupae found in each fruit. Based on their characteristics, it can be inferred that star fruit and papaya are softer than guava, mango, and water apple. The host preferences of these fruit flies are driven by a combination of visual cues and chemical signals emitted by the fruits, which attract them to optimal sites for oviposition. The host selection processes of *B. carambolae* and *B. papayae* are primarily driven by

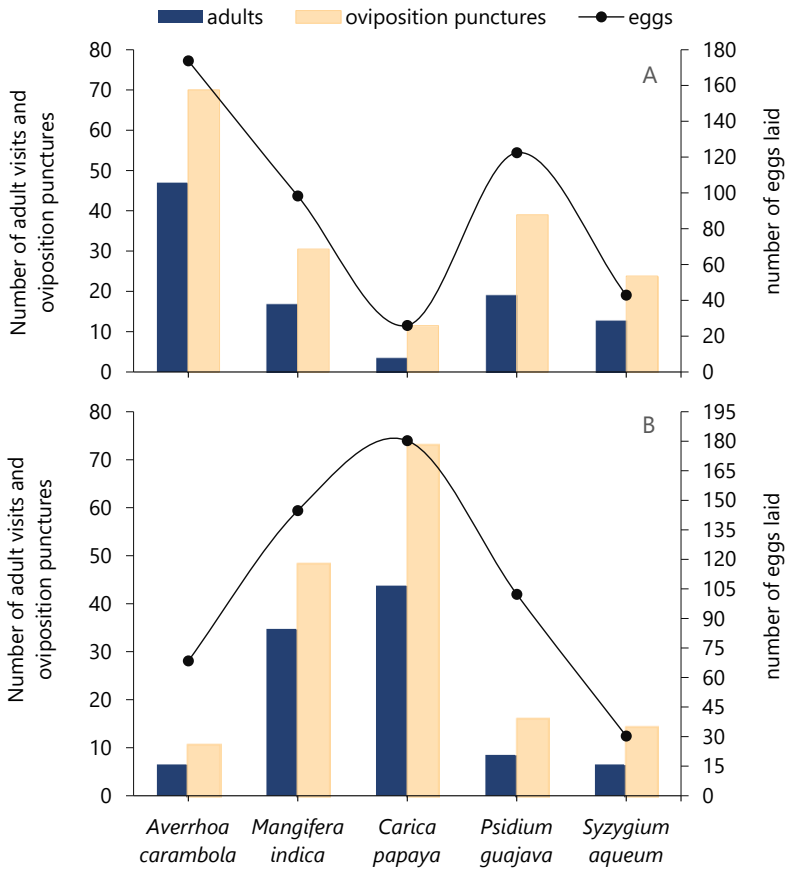

Fig. 9: Number of adults visits, oviposition punctures, and eggs laid of *B. carambolae* (a) and *B. papayae* (b) on several host plants in the laboratory.

Table 2: Fruit fly preference and performance survival from pupa to adult on a several host plant in the laboratory

Host plant	Pupae number	Pupa period (days)	Adults emerged (flies)	Adults emerged (%)	Female number	Male number
Bactrocera carambolae						
A.carambola	49.50 ± 1.44 a	7.25 ± 0.25 ab	44.75 ± 1.54 a	90.40 ± 1.00 a	28.25 ± 0.62 a	15.75 ± 1.37 a
C. papaya	10.50 ± 0.95 c	8.50 ± 0.28 a	6.00 ± 0.40 c	57.70 ± 2.70 c	4.00 ± 0.00 d	2.25 ± 0.25 c
S. aqueum	11.75 ± 0.47 c	8.25 ± 0.25 ab	6.75 ± 0.47 c	57.37 ± 3.11 c	4.50 ± 0.28 d	2.25 ± 0.25 c
M. indica	24.25 ± 0.94 b	7.00 ± 0.48 b	19.25 ± 1.03 b	79.37 ± 2.88 ab	12.00 ± 0.70 b	7.00 ± 0.40 b
P. guajava	20.50 ± 1.04 b	7.75 ± 0.25 ab	15.75 ± 0.47 b	77.15 ± 2.73 b	9.50 ± 0.28 c	6.25 ± 0.47 b
Bactrocera papayae						
A.carambola	19.00 ± 1.08 b	8.75 ± 0.25 a	11.00 ± 0.70 c	57.90 ± 1.81 b	7.25 ± 0.47 c	3.75 ± 0.25 c
C. papaya	42.50 ± 1.19 a	7.25 ± 0.25 b	36.50 ± 0.86 a	85.95 ± 1.66 a	27.50 ± 0.64 a	9.00 ± 0.81 a
S. aqueum	19.50 ± 0.64 b	8.75 ± 0.25 a	14.00 ± 0.40 c	71.95 ± 2.57 b	7.50 ± 0.28 c	6.50 ± 0.28 b
M. indica	39.25 ± 0.94 a	7.25 ± 0.25 b	32.25 ± 0.47 b	82.35 ± 2.90 a	23.25 ± 0.47 b	9.00 ± 0.40 a
P. guajava	22.50 ± 0.64 b	8.50 ± 0.28 a	14.00 ± 1.08 c	62.10 ± 3.95 b	8.75 ± 0.85 c	5.25 ± 0.47 bc

Means (± SE) in one column followed by the same letters have no significant difference at the 5% level according to the Tukey HSD test.

a mix of olfactory and visual factors, the accessibility of host plants, and several environmental influences. The host selection and oviposition behaviors of these fruit fly species are influenced by fruit characteristics, including texture, aroma, odor, color, and nutrient content at all ripeness stages (Fitrah *et al.,* 2021; Grechi *et al.,* 2021; Saeed *et al.,* 2022). Furthermore, the nutritional characteristics of fruits play a significant role in shaping the preferences and growth patterns of fruit flies, which rely on these resources for energy and nourishment throughout their life cycle until they become adults (Theron *et al.,* 2017; Roh *et al.,* 2021; Saeed *et al.,* 2022). These factors play important roles in determining the suitability of a host for egg-laying and following larval development.

This study demonstrated that the quantity of ovipositor punctures on the sampled fruit aligns with the number of fruit flies lured to the host fruit jars, suggesting that the attraction to the host fruit is a precursor to oviposition. The number of ovipositor punctures by *B. carambolae* is higher on star fruit, while *B. papayae* exhibits a more significant number of papaya. There is a direct correlation between the amount of ovipositor punctures and the quantity of eggs that are laid. Star fruit and papaya are selected as oviposition sites by *B. carambolae* and *B. papayae*, respectively, indicating that the texture of these fruits is suitable for egg-laying. It has been found that fruit flies prefer to oviposit on host plants they odor (Roh *et al.,* 2021; Saeed *et al.,* 2022). Several determinants can shape oviposition preferences, including climatic conditions, the specific location, the size and color of the fruit, as well as its flavor (Muryati *et al.,* 2017; Fitrah *et al.,* 2021; Saeed *et al.,* 2022). Larger fruits accompanied by appealing odor, colors, and shapes are more prone to infestation by fruit flies (Roh *et al.,* 2021; Dias *et al.,* 2022). The results indicate that star fruit is the preferred host for *B. carambolae*, while *B. papayae* shows a strong preference for papaya compared to all other tested fruits under laboratory conditions. There were no significant differences observed in the pupal development period across the different fruit hosts. However, water apple was found to be the least preferred compared to star fruit, guava, mango, and papaya. The present study demonstrates a correlation between the number of eggs laid, pupae formation, and adult fruit flies' emergence. In fruits favored and selected as oviposition and pupation sites, more adult fruit flies emerge than other fruits. The homogeneous conditions in the laboratory support the development of fruit flies on host fruits, as biotic environmental factors, such as the population suppression of fruit flies by natural enemies, do not influence them. By providing controlled environmental conditions akin to those in a laboratory, the transformation of pupae into adult fruit flies can be effectively supported (Saeed *et al.,* 2022; Susanto *et al.,* 2022). Additionally, host plants' physical characteristics and chemical compound content significantly influence the development and biology of fruit flies within their hosts (Fitrah *et al.,* 2021; Roh *et al.,* 2021). This phenomenon has the potential to alter the behavior of fruit flies with respect to their feeding, reproduction, mating, and dispersal activities (Saeed *et al.,* 2022; Pogue *et al.,* 2024). The availability of alternative wild and cultivated host plants also significantly influences the survival, dispersal, and population density of *B. carambolae* and *B. papayae*. These fruit flies are polyphagous, meaning they can utilize a wide range of host plants, which has the potential for population expansion and enhances their adaptability (Vargas *et al.,* 2015; Masseliere *et al.,* 2016). Having a range of host plants secures a consistent supply of resources necessary for sustenance and oviposition. The availability of alternative host plants simplifies and facilitates the dispersal of fruit fly populations into new areas. When these flies encounter suitable host plants in different regions, they can form new populations, expanding their geographic range.

Fruit fly parasitoids

During the study, it was found that the natural enemies that developed from the infested fruits were predominantly parasitoids. Notably, these parasitoids were absent from certain host fruits. Four species of parasitoids were identified on several types of fruit, including star fruit, guava, and mango. These parasitoid species were *Biosteres* sp., *Opius* sp., *Diachasmimorpha longicaudata*, and *Fopius arisanus*, all belonging to Hymenoptera and the family Braconidae. These four parasitoids are classified as larval-prepupal endoparasitoids of Tephritid fruit flies, and they emerge from pupae that have been collected from pupae collected from star fruit, mango, and guava. Among the four, *D. longicaudata* and *F. arisanus* had relatively high proportions, accounting for 20.40% and 12.70%, respectively (Table 3). The parasitoid parasitism rate was highest in star fruit (45.99%)

and lowest in mango (17.48%). *D. longicaudata* and *F. arisanus* consistently emerged from each host plant, with varying population and parasitism rates, suggesting competition between these parasitoids in parasitizing *B. carambolae* and *B. papayae* fruit flies. Additionally, several fruit fly pupae experienced mortality during rearing due to factors such as fungal infections, desiccation, or parasitism, especially in guava and mango, where the parasitoid did not successfully develop inside the pupa. Furthermore, these findings highlight the potential of *D. longicaudata* and *F. arisanus* as effective biological control agents, but their success may depend on host fruit availability, competition, and environmental conditions.

The fruit fly parasitoids identified in this study belong to the family Braconidae and include four genera: *Biosteres* sp., *Opius* sp., *D. longicaudata*, and *F. arisanus*. These parasitoids are endobionts that typically parasitize fruit flies during their immature stage and emerge during the pupal stage of fruit fly metamorphosis. The most commonly observed parasitoids in the infested fruit were *D. longicaudata* and *F. arisanus*. These species play a critical role in parasitizing *B. carambolae* and *B. papayae*, exhibiting relatively high parasitism rates compared to other parasitoids such as *Opius* sp. and *Biosteres* sp. The parasitism rates of *D. longicaudata* and *F. arisanus* were highest in *A. carambolae* compared to other hosts, indicating that *A. carambolae* is a more suitable host for developing these parasitoids. Host availability, which includes aspects like fruit morphology, climatic elements (temperature and rainfall), habitat suitability, and the density of fruit flies, played a significant role in shaping parasitoid preferences and parasitism rates. According to Miranda *et al.* (2015), parasitoids preferentially target fruit fly-infested plants with thin and soft skins, such as *A. carambolae*, *P. guajava*, and *M. indica*, as these characteristics facilitate the parasitism of larvae or eggs of the fruit flies. Furthermore, Ovruski *et al.* (2009) indicated that climatic conditions, including rainfall, can impact the presence and parasitism rates of fruit fly parasitoids by affecting their mobility. The presence of the parasitoids *Diachasmimorpha longicaudata* and *Fopius arisanus* on various host plant species, along with varying populations and parasitism rates, indicates competition between these parasitoids for parasitizing *B. carambolae* and *B. papayae*. The interaction between these two parasitoids influences their efficacy as biological control agents against Bactrocera species. *F. arisanus* parasitizes fruit fly eggs, while *D. longicaudata* targets larvae, creating a complementary control strategy (Haryono *et al.,* 2016; Susila and Supartha, 2020; Dias *et al.,* 2022). However, competition may arise if *D. longicaudata* attempts to parasitize hosts already infected by *F. arisanus*. The process of niche partitioning lessens direct competition, and the simultaneous presence of these species can lead to greater efficiency in pest management. Environmental factors and host availability further influence their success, underscoring the need to optimize release strategies for effective and sustainable pest control (Miano *et al.,* 2022). It aligns with the findings by Vargas *et al.* (2013) and Miranda *et al.* (2015), which suggest that interspecific competition can occur between two coexisting parasitoid species. Across all the fruits analyzed, *D. longicaudata* exhibited a higher parasitism rate compared to *F. arisanus*. This finding contrasts with several studies conducted in Bali, which reported lower parasitism rates for *D. longicaudata* compared to *F. arisanus* on various Bactrocera species infesting guava, mango, and star fruit (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019; Yuliadhi *et al.,* 2022). Successful management of Bactrocera fruit flies

Table 3: Number of parasitoids, fruit flies (± SE), and parasitism levels of fruit fly parasitoids on star fruit, guava, and mango in the field (n=100 pupae)

Variabel		*A.carambolae*	*P. guajava*	*M. indica*
Parasitoid	*Biosteres* sp.	3.30 ± 0.51	0	1.10 ± 0.31
	Opius sp.	7.60 ± 0.51	5.70 ± 0.63	0
	D. longicaudata	20.40 ± 0.21	12.10 ± 0.22	7.40 ± 0.22
	F. arisanus	12.70 ± 0.26	7.60 ± 0.27	8.20 ± 0.25
Fruit flies	*B. carambolae*	42.10 ± 0.30	46.80 ± 0.65	49.40 ± 0.54
	B. papayae	11.40 ± 0.21	16.10 ± 0.41	18.70 ± 0.80
	Parasitization (%)	45.99	26.52	17.48
	Not emerged (%)	0	9.50 ± 1.05	13.20 ± 0.81

using parasitoids depends on the careful selection of appropriate species, confirming host compatibility, refining release techniques, and taking environmental factors into account. Mass-rearing and augmentation enhance effectiveness by providing a steady parasitoid supply, preserving quality, enabling precise releases, and aligning with the Bactrocera population surge for better suppression and sustainability (Garcia and Ricalde, 2013; Larasati *et al.,* 2013; Miranda *et al.,* 2015). The elevated population and parasitism levels of *D. longicaudata* relative to *F. arisanus* may stem from its improved ability to detect hosts on infested fruits, including those that have dropped to the ground. The parasitism rates of the parasitoids *Biosteres tryoni* and *D. longicaudata* were higher on fallen, decaying fruit infested by fruit flies (Haryono *et al.,* 2016; Setiawan *et al.,* 2024). Additionally, Vargas *et al.* (2013) found that *F. arisanus* exhibited a significantly lower parasitism rate on fallen fruit than on the tree, indicating a preference for oviposition on fruit that remains attached. Furthermore, the parasitism rate of *Fopius* sp. on five species of Bactrocera was lower than that of *Biosteres* sp. (Haryono *et al.,* 2016; Ardiyanti *et al.,* 2019). The successful implementation of environmentally sustainable pest management relies heavily on the detection and identification of parasitoid species associated with pest populations. These findings provide new perspectives into Indonesia's fruit fly management strategies, emphasizing parasitoid augmentation integration with other sustainable control methods for enhanced effectiveness and long-term pest suppression. In agricultural fields, the control of fruit flies remains largely dependent on synthetic insecticides. While these chemicals are crucial for controlling Bactrocera species, increasing insecticide resistance highlights the need for integrated alternative strategies to ensure sustainable and effective pest control (Li *et al.,* 2024; Akram *et al.,* 2024). To enhance integrated pest management (IPM), it is essential to implement monitoring techniques, biological control approaches, and cultural practices that responsibly manage fruit fly populations in an eco-friendly manner. Incorporating remote sensing technology and artificial intelligence enhances pest control's precision, efficiency, and effectiveness while minimizing economic losses and environmental harm (Lello *et al.,* 2023). Educating farmers and stakeholders through IPM training and adopting eco-friendly strategies promotes sustainable fruit fly control and reduces dependence on chemical pesticides (Niassy *et al.,* 2022; Dias *et al.,* 2022; Dominiak and Follett, 2024). Utilizing fruit fly traps that are baited with methyl eugenol represents one of the most affordable and sustainable methods for monitoring. Data collected from these traps can support the development of predictive models, strengthen early warning systems, and ultimately decrease crop damage and reliance on chemical control measures.

CONCLUSION

This study confirms that *Bactrocera carambolae* and *Bactrocera papayae* are the dominant fruit fly species affecting fruit cultivation in Indonesia, particularly in West Java Province. In their respective environments, both species reveal specific host preferences; *B. carambolae* is particularly attracted to star fruit, whereas *B. papayae* tends to favor papaya. Laboratory experiments further confirm that fruit characteristics such as texture, odor, and nutrient content influence fruit fly oviposition and development. Star fruit and papaya were identified as the most suitable hosts for *B. carambolae* and *B. papayae*, respectively, as these fruits supported higher egg-laying, pupation, and adult emergence rates compared to other fruit types. urthermore, the presence of host plants is essential in influencing infestation patterns, which in turn has a significant impact on the dynamics of fruit fly populations. Regions that have a plentiful supply of preferred host fruits typically encounter elevated infestation rates, since these plants supply crucial resources for the reproduction, development of larvae, and overall survival of fruit flies. The presence of suitable host plants attracts adult fruit flies and sustains population growth by offering optimal conditions for egg-laying and larval nourishment. The significant reliance on the availability of host plants highlights the necessity for strategic pest management strategies, including crop diversification and synchronized harvesting, to interrupt the breeding cycles of fruit flies and effectively mitigate infestations. Ecological factors, particularly rainfall and temperature, also play a pivotal role in regulating the population dynamics of these fruit fly species. *Bactrocera carambolae* reaches peak abundance during the rainy season, benefiting from increased moisture and humidity, while *Bactrocera papayae* thrives in warmer conditions, indicating a strong preference for higher temperatures. The evident connection between

fruit fly populations and environmental variables emphasizes the important role that climate plays in their distribution and growth patterns. Increased rainfall fosters favorable conditions for *B. carambolae* by enhancing host fruit availability and improving larval survival rates. In contrast, elevated temperatures accelerate the development, reproduction, and overall abundance of *B. papayae*. These findings highlight the necessity of integrating climatic variables into fruit fly management approaches, especially in areas undergoing seasonal variations in rainfall and temperature. Additionally, four parasitoid species were identified, with *Diachasmimorpha longicaudata* and *Fopius arisanus* exhibiting notably high parasitism rates in the field. This suggests that these parasitoids could serve as significant mortality factors for *B. carambolae* and *B. papayae*. The conclusions drawn from this study underscore the importance of adopting effective strategies for managing fruit flies in the agricultural sector focused on fruit production. Monitoring techniques, such as methyl eugenol traps, have proven effective in tracking and reducing fruit fly populations. To effectively manage pests, an integrated approach should evaluate seasonal variations, host plant preferences, and environmental factors, aiming to reduce infestations, minimize agricultural losses, and foster ecological sustainability. Further research is recommended to study and culture the four parasitoid species of *B. carambolae* and *B. papayae* found in West Java Province, to optimize augmentative biological control strategies for fruit flies.

AUTHOR CONTRIBUTIONS

D. Koswanudin conceptualized the research idea, designed the study, conducted investigations, performed literature reviews, curated data, and secured funding. H. Widyanto contributed to the design and conceptualization of the manuscript, conducting investigations, curating data, performing literature reviews, analysis, and interpretation of data. D. Hutapea contributed to the acquisition of data, analysis and interpretation of data, statistical analysis, and manuscript preparation and helped improve the manuscript. Wawan contributed to conducting investigations, acquiring data, and drafting the manuscript. R. Yuniawati contributed to performing literature reviews, curating data, and obtaining funding. V.N.O. Subagyo contributed to the data visualization and manuscript preparation and its improvement. S. Utami contributed to the acquisition of data, analysis, interpretation of data, statistical analysis, and drafting of the manuscript, and helped improve the manuscript. I. M. Samudra contributed to designing the study, supervising, preparing, and improving the manuscript. W. Darwiati performed the literature reviews and contributed to manuscript preparation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius

ANOVA	Analysis of variance
AQIS	Australian Quarantine and Inspection Service
cm	Centimeters
CSAI	Central Statistic Agency of Indonesia
Fig.	Figure
GDP	Gross domestic product
GLM	Generalized linear model
h	Hours
ha	Hectare
HSD	Honestly Significant Difference
IPM	Integrated pest management
m²	Square meters
mm	Millimeters
pH	Potential of Hydrogen
R2+3	Wing vein ending at the anterior apical third of the wing
R^2	R squared (the coefficient of determination)
SE	Standard error
Tav	Average temperature
Tmax	Maximum temperature
Tmin	Minimum temperature
USD	United States Dollar
w/w	Weight per weight
X1	Maximum temperature
X2	Minimum temperature
X3	Average temperature
X4	Rainfall
y	Year

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