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Effects of meliponiculture *Tetragonula laeviceps* on pollinator diversity and visitation rate and citrus productivity in West Java, Indonesia

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Abstract. *Nurdiansyah MA, Abduh MY, Permana AD. 2023. Effects of meliponiculture* Tetragonula laeviceps *on pollinator diversity and visitation rate and citrus productivity in West Java, Indonesia. Biodiversitas 24: 5757-5763. Citrus reticulata* var. *Rimau Gerga Lebong* (*RGL*) is a prominent Indonesian citrus variety, yet its global productivity is facing challenges due to decreasing diversity in pollinators. This study aimed to bolster the productivity of *C. reticulata* var. *RGL* in Bandung by introducing *Tetragonula laeviceps* Smith 1857 (Hymenoptera: Apidae). Simultaneously, the study explored the influence of pollinator diversity, foraging behavior, and visitation rates and compared the results with open and wind pollination. Field investigations were conducted to observe the pollination activities of *T. laeviceps* and eight wild pollinator species, including *Apis cerana* Fabricius 1793, *Ceratina cognata* Smith 1879, *Xylocopa confusa* Pérez 1901, *Xylocopa latipes* Drury 1773, *Vespa affinis* Linnaeus 1764, *Dolichoderus thoracicus* Smith 1860, *Papilio demoleus* Linnaeus 1758, and *Catopsilia pyrantel* Linnaeus 1758. *T. laeviceps* exhibited the highest relative abundance (34.87%) and an average time spent of 72.11 seconds per flower. Visitation rates were highest during noon (10:00 to 13:00) at 0.31 pollinators/hour/flower, influenced by temperature, relative humidity, and light intensity. The phenological stages of *C. reticulata* var. *RGL* spanned 240 days. Fruit set, fruit weight, and estimated citrus productivity were significantly higher in *T. laeviceps* and open pollination compared to wind pollination. This study highlights the suitability of *T. laeviceps* as an effective pollinator for *C. reticulata* var. *RGL*. The findings have implications for the conservation and management of pollinator populations to ensure sustainable citrus production in the declining global diversity.

Keywords: Phenological stages, pollination, productivity, relative abundance, time spent

INTRODUCTION

Citrus production is vital to global agriculture, contributing significantly to the world's agricultural output. In 2020, global citrus production amounted to 75,458,588 tonnes, albeit with a slight decline of 0.71% (FAO 2021). However, Indonesia's citrus industry faced a more substantial setback in 2021, where citrus production plummeted by 7.42%, marking the most significant decline in the past five years (Statistics Indonesia 2021). This decline can be attributed, in part, to the reduction in citrus orchards spanning from 2014 to 2020, with a net loss of 276,097 ha (FAO 2021). The overarching issue of climate change casts considerable uncertainty on agricultural production worldwide, impacting critical factors such as soil conditions, water availability, temperature patterns, atmospheric CO_2 levels, and the prevalence of pests and plant diseases (Kumar and Raj Gautam 2014; Flaig 2021). These climatic shifts can disrupt the delicate balance of agricultural ecosystems, causing ripples across various crops, including citrus.

Simultaneously, climate change and land use alterations can exert significant pressure on wild pollinators, including honeybees. These pollinators depend on nectar and pollen sources that may become scarce due to changes in floral composition and abundance (Potts et al. 2017). Honey bee, such as European (*Apis mellifera* Linnaeus 1758) in Brazil, Mexico, and Pakistan (Malerbo-Souza et al. 2004; Grajales-Conesa et al. 2013; Haq et al. 2016), Red Dwarf (*Apis florea* Fabricius 1787) in Pakistan (Mehmood et al. 2015), and Asian (*Apis cerana* Fabricius 1793,) in India and Indonesia, play a pivotal role in pollinating citrus flowers across the globe (Haq et al. 2016; Pradhan and Devy 2019; Cholis et al. 2020). However, overreliance on a single pollinator species carries inherent risks.

Increasing evidence suggests that a higher diversity of wild pollinators in agricultural landscapes positively correlates with enhanced fruit set percentages. The rate of fruit set itself is contingent on the frequency of pollinator visits to plant flowers (Gallagher and Campbell 2020). One promising approach to bolstering pollinator diversity and abundance on agricultural lands is the cultivation of colony bees, selected based on morphological traits, adaptability, and activity levels.

Many studies conducted in citrus orchards have underscored the significance of wild stingless bees as the primary pollinators following honeybees (Grajales-Conesa et al. 2013; Mehmood et al. 2015; Haq et al. 2016; Azmi et al. 2019; Pradhan and Devy 2019; Cholis et al. 2020). Stingless bees substantially augment fruit productivity in open and closed agricultural systems (Nunes-Silva et al. 2013; Putra et al. 2014, 2022; Azmi et al. 2017, 2019). Among these, *Tetragonula laeviceps* Smith 1857 emerges as a prominent candidate for domestication in Indonesia (Buchori et al. 2022). With its diminutive size (less than 0.5 cm) and impressive adaptability in new environments, *T. laeviceps* is promising as an effective pollinator for citrus flowers (Putra et al. 2014; Haq et al. 2016; Efin et al. 2019).

This study applied the meliponiculture of *T. laeviceps* in *Citrus reticulata* var. *Rimau Gerga Lebong* orchards, aiming to gauge its adaptability, pollination activity, and impact on citrus plants. The study investigates the diversity and relative abundance of citrus-pollinating insects, utilizing population data to assess their adaptability. Additionally, the foraging behavior of these pollinators is scrutinized based on time spent and visitation rates as activity parameters. The study also delves into the percentage of fruit set and estimates the impact on citrus fruit productivity. Introducing *T. laeviceps* through meliponiculture is anticipated to demonstrate adaptability in citrus orchards, while concurrently preserving the diversity of wild pollinators and enhancing the citrus fruit set. This research seeks to contribute valuable insights into sustainable citrus production strategies, aligning with global efforts to address declining citrus yields and pollinator diversity.

MATERIALS AND METHODS

Study site

The study was conducted at Bukit Sandy, Bandung District, West Java, Indonesia, at coordinates 6°51'32" S latitude, 107°39'27" E longitude, and an altitude of 1,078 meters above sea level. The study area encompassed a total of 1.5 hectares with the western section is a residential area divided by roads, the eastern and northern sections are pine forests, and the southern section is a horticultural garden. The citrus variety under investigation was *Citrus reticulata* var. *Rimau Gerga Lebong*, aged 4 years, with an average height of 3 meters and a canopy width of 2 meters. Data collection occurred over a year, from September 2021 to August 2022, with the peak flowering period for citrus plants occurring between 12 December and 27 December 2021. Local environmental conditions during this period, including temperature, relative humidity, and light intensity, were recorded using a Data Logger HOBO U10-003.

Procedures

Experimental design

This study was initiated in September 2021 by cultivating 15 colonies of *T. laeviceps* into a citrus orchards at Mekarsaluyu, Bandung District, West Java, Indonesia. Each colony had a population ranging from 400 to 600 bees. The colonies were acclimatized for 3 months within the citrus orchards. To evaluate the activity of *T. laeviceps* and other pollinators visiting *C. reticulata* var. *RGL* flowers, two plots, each measuring 20×20 m² and containing 20 plants per plot, were designated for observations. Observations occurred every hour from 07:00 to 17:00 and lasted for 15 minutes. The study aimed to assess the impact of *T. laeviceps* on *C. reticulata* var. *RGL* pollination through 3 distinct treatments: wind pollination, open pollination, and *T. laeviceps* pollination, with 4 replicates each. For the wind and *T. laeviceps* pollination treatments, insect net covers (2×2×3 m³) with a mesh size of 36 mm were employed to prevent wild pollinators from interacting with the plants. In the case of the *T. laeviceps* pollination treatment, a *T. laeviceps* colony was placed inside the net at 1 meter above the ground. After the flowering phase concluded, the insect net covers were removed to facilitate plant growth and development, allowing *T. laeviceps* to forage for pollen and nectar from other plants.

Diversity, relative abundance, and foraging behaviors of pollinators on citrus flowers

Wild pollinator insects were collected by sweep net (mesh size 0.9×0.3 mm) using a dried preservation technique and subsequently pinned. These specimens were sent to the Laboratory of Entomology, School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia for taxonomic identification. The foraging behavior of pollinators was observed through a scan sampling method on the two designated plots, with observations lasting 15 minutes per plot every hour from 07:00 to 16:00 (Cholis et al. 2020; Gallagher and Campbell 2020). The diversity of pollinators was assessed through percentage relative abundance calculations by the total number of each pollinator species per total number of pollinators, multiplied by 100%. The time spent by each pollinator visiting citrus flowers was recorded using focal sampling (Putra et al. 2014).

Pollinator visitation rates on citrus flowers

The pollinator visitation rate was documented every three days during the blooming stages, specifically at three intervals: 07:00-10:00 (morning), 10:00-13:00 (noon), and 13:00-16:00 (afternoon). Visitations were observed through a scan sampling method on the designated plots, with observations lasting 15 minutes per plot every hour. The pollinator visitation rate was calculated as the number of pollinators visited flowers divided by the number of flowers available per observation (Gallagher and Campbell 2020).

Phenological stages, pollination success, and productivity of citrus

Phenological stages of *C. reticulata* var. RGL were monitored, with 30 flowers examined at each stage, including bud break, petal elongation, pre-bloom, full bloom, petal fall, fruit set, fruit development, and mature fruit (Shafqat et al. 2021). The fruit set stage was especially important because it represented a critical transition from flower to fruit and was influenced by pollination. Pollination success was determined by calculating the percentage of fruit set as the total number divided by the total number of flowers, multiplied by 100% (Azmi et al. 2019; Gallagher and Campbell 2020). Furthermore, citrus productivity was estimated based on the number of fruit sets, fruit count, and average fruit weight, considering a spacing of 4×4 m², resulting in 625 plants per hectare and assuming a single harvest per year. The estimate was calculated by multiplying the weight of the fruits per plant by the number of plants.

Data analysis

All collected data were subjected to tests for normality and homogeneity of variance, and no data transformation was deemed necessary. One-way ANOVA and Tukey's post hoc test were employed to analyze variables such as time spent, citrus flower count, number of fruit sets, and the percentage of fruit set. Additionally, correlations between the number of fruit sets, marketable fruit count, fruit weight, and estimated citrus productivity were investigated through ANOVA. Pearson correlation analysis assessed the correlation between visitation rates, the number of fruit sets, and the highest percentage of fruit sets (Tschoeke et al. 2015). Statistical analyses were conducted using IBM SPSS Statistics (version 25.0: 2018). Finally, principal component analysis (PCA) was employed to explore correlations between microclimate conditions (temperature, relative humidity, and light intensity) and visitation rates, utilizing Paleontological Statistics (PAST) software.

RESULTS AND DISCUSSION

Microclimate conditions

The study spanned from September 2021 to August 2022, and the recorded microclimate data is illustrated in Figure 1. Monthly temperature ranged from 19.15-21.72°C (minimum) to 24.22-27.49°C (maximum), with the highest precipitation occurring in December 2021, totaling 2,057 mm annually (Figure 1.A). The peak blooming season of *Citrus reticulata* var. *Rimau Gerga Lebong* fell between 12 December and 27 December 2021, coinciding with observations of pollinator diversity and visitation rates.

During the blooming season, microclimate conditions (Figure 1.B) exhibited temperatures between 25.36-29.82°C, relative humidity levels ranging from 57.74-85.31%, and an average light intensity of 740.33-9,329.33 lux. These temperature conditions align well with the optimal range of 18-34ºC for most stingless bee species, promoting the growth of *T. laeviceps* colonies and encouraging active foraging for pollen, nectar, and resin (Grüter 2020).

Diversity, relative abundance, and foraging behaviors of pollinators

Observations identified *T. laeviceps* and 8 other pollinator species (Table 1) visiting citrus flowers. Hymenoptera species, including *Tetragonula laeviceps*, *Apis cerana*, *Ceratina cognata* Smith 1879, *Xylocopa confusa* Pérez 1901, and *Xylocopa latipes* Drury 1773, approached flowers from the front and typically landed on the petals. In contrast, butterfly species such as *Papilio demoleus* Linnaeus 1758 and *Catopsilia pyrantel* Linnaeus 1758 approached flowers from above and landed directly on the stamen. Wild pollinator insects play crucial roles in agricultural ecosystems, with higher diversity and relative abundance generally positively influencing fruit sets, especially wild bees (Nicodemo et al. 2013; Tschoeke et al. 2015).

This study identified 9 pollinator species, with stingless bees *T. laeviceps* exhibiting the highest relative abundance of 34.87%. However, previous research has reported stingless bees ranking second to honey bees for crops like watermelon, chili, and melon (Koffi et al. 2013; Putra et al. 2014; Tschoeke et al. 2015). Pollinator diversity in *C. reticulata* var. *RGL* orchard is high and close pollinator species observed for the orchards of *C. maxima* as many as (Cholis et al. 2020), 8 to 10 pollinator species for *C. limon* (Mehmood et al. 2015; Layek et al. 2020), 7 pollinators species for *C. sinensis* (Grajales-Conesa et al. 2013), and can reach up to 24 pollinator species in *C. reticulata* in India (Pradhan and Devy 2019). This suggests that the agroecosystem factors influence pollinator diversity.

Foraging behaviors of the pollinators varied, with honeybees primarily foraging for nectar and pollen from citrus flowers from 08:00-12:00 (Figure 2.A), while stingless bees, like *T. laeviceps*, began foraging from 09:00-14:00. The peak visitation rate for *A. cerana* was at 10:00 with 23 bees. In comparison, for *T. laeviceps*, it occurred at 11:00 with 39 bees in the first 30 minutes. *T. laeviceps* typically forage for nectar and pollen later than other insects, between 10:00-13:00, which aligns with previous observations (Putra et al. 2014; Cholis et al. 2020; Abduh et al. 2023) and the same as other species (Nicodemo et al. 2013). This is because the first activity of stingless bees is looking for resin (Grüter 2020) to produce propolis six times more than the honey bees (Kothai and Jayanthi 2015; Abduh et al. 2020).

The shortest time spent on citrus flowers is 37.33 seconds, as recorded by *D. thoracicus* (P-value <0.05), and the longest is 72.11 seconds, as recorded by *T. laeviceps* (P-value <0.05). Others spent relatively the same amount of time (Figure 2.B). Although *T. laeviceps* takes more time to pollinate citrus flowers, it exhibited the highest relative abundance of 34.87%. The time spent by *T. laeviceps* in one flower is relatively longer than other pollinators (Putra et al. 2014). Other studies have reported that stingless bees spend more time collecting nectar and pollen than honey bees (Putra et al. 2014; Gallagher and Campbell 2020; Layek et al. 2021). According to observations in the field, *T. laeviceps* is very slow and preferentially carries pollen.

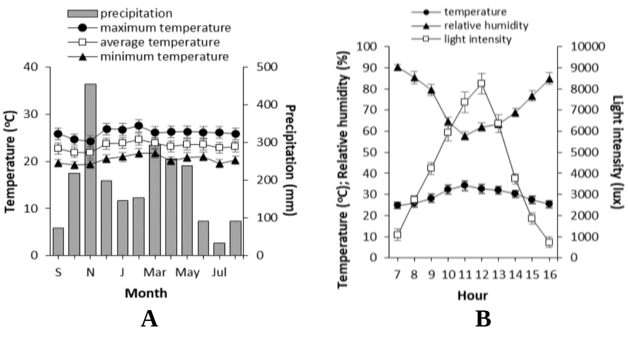
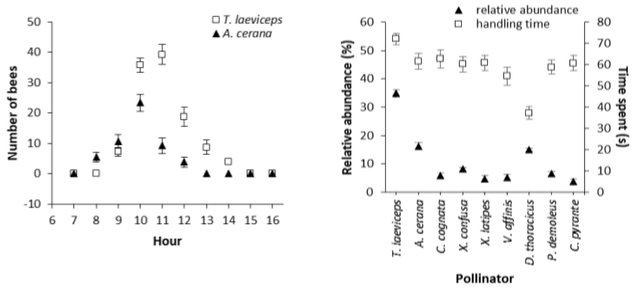


Figure 1. Microclimate conditions. A. Minimum, maximum, and average temperatures ± SD and precipitation for September 2021-August 2022; B. Average temperature, relative humidity, and light intensity on the days (blooming season) ± SD



A B

Figure 2. Diversity of pollinators. A. Foraging behavior of *T. laeviceps* and *A. cerana* ± SD; B. Percentage of relative abundance and time spent by pollinators ± SD

Pollinator visitation rate on citrus flowers

The visitation rate of pollinators shows the number of flowers a pollinator visits per hour (Figure 3.A). The three categories of visitation rates showed significant differences, with the highest average visitation rate occurring at noon (10:00 to 13:00), reaching 0.31 pollinators/hour/flower (P-value <0.05), and the lowest rate in the afternoon (13:00 to 16:00) at 0.07 flower/hour (P-value <0.05). The morning (7:00 to 10:00) exhibited an average visitation rate of 0.15 flowers/hour (P-value <0.05). The peak visitation rate at 10:00-13:00 corresponds to the period when most pollinators are actively foraging, and citrus blossoms are in full bloom (approximately 09:00-10:00) (Grajales-Conesa et al. 2012; Haq et al. 2016; Shafqat et al. 2021). Higher volatile organic compound emissions during full bloom attract more pollinators (Raguso 2008; Klatt et al. 2013).

The peak visitation rate coincided with the 15th day, displaying a strong positive correlation with the highest number of citrus flowers (r = 0.65, P-value = 0.04). After three days, pollinator visits led to 3,746 fruit sets from 40 plants with 5,376 flowers, resulting in a success rate of 69.68%. The percentage of fruit set during the blooming season showed no significant variation (P-value >0.05). The highest percentage of fruit set, 70.31%, occurred on the 18th day (Figure 3.B), exhibiting a strong positive correlation with the average highest visitation rate on the 15th day (r = 0.72, P-value = 0.02). A higher visitation rate enhances the percentage of fruit set as it increases the likelihood of fertilization (Nunes-Silva et al. 2013; Putra et al. 2014; Tschoeke et al. 2015; Gallagher and Campbell 2020; Layek et al. 2020). Using *T. laeviceps* as a pollinator yielded a high fruit set in citrus, similar to other plants, with success rates of 50-70% (Putra et al. 2014, 2022).

Correlations between microclimate conditions with visitation rate of pollinators

Visitation rates correlated with microclimate conditions such as temperature, relative humidity, and light intensity. Visitation rate and temperature exhibited a strong positive correlation (r = 0.62, P-value = 0.03), while visitation rate and light intensity also displayed a relatively strong positive correlation (r = 0.48, P-value = 0.02). In contrast, visitation rate and relative humidity had a strong negative correlation (r = -0.63, P-value = 0.03). Principal component analysis revealed that temperature exerted the most significant influence on the visitation rate of pollinators (Figure 4).

Microclimate conditions, including temperature, relative humidity, and light intensity, collectively influenced pollinator visitation rates (Polatto et al. 2014). Temperature and light intensity correlate positively with visitation rates (Taha et al. 2016), whereas relative humidity and visitation rates are negatively correlated (Taha et al. 2016; Cholis et al. 2020). The temperature component has the closest distance to the visitation rate, so the temperature substantially influences pollinators visiting citrus flowers. Many studies reported that the temperature influences pollinators visiting flowers as the main component (Polatto et al. 2014; Taha et al. 2016; Gallagher and Campbell 2020; Layek et al. 2020; Trianto and Purwanto 2022). This means that significant fluctuations in temperature will influence pollinator visitation rates on citrus flowers.

Table 1. Percentage relative abundance (%) of citrus flower pollinators during the anthesis period

Hour	Hymenoptera							Lepidoptera	
	Apidae					Vespidae	Formicidae	Papilionidae	Pieridae
	T. laeviceps	*A. cerana*	*C. cognata*	*X. confusa*	*X. latipes*	*V. affinis*	*D. thoracicus*	*P. demoleus*	*C. pyrante*
07:00	0	0	0	0	0	0	0	0	0
08:00	0	17.10	12.44	18.65	8.29	7.25	17.62	10.88	7.77
09:00	11.94	17.78	11.67	10.56	6.39	6.94	20.00	8.89	5.83
10:00	31.06	20.32	4.64	9.00	6.10	5.08	14.80	5.37	3.63
11:00	53.17	12.44	2.71	4.98	2.26	3.62	11.76	6.56	2.49
12:00	59.57	12.23	2.66	0	0	5.32	17.02	3.19	0
13:00	100	0	0	0	0	0	0	0	0
14:00	100	0	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0	0	0

Notes: The number of pollinators visiting citrus flowers is 1,947 pollinators

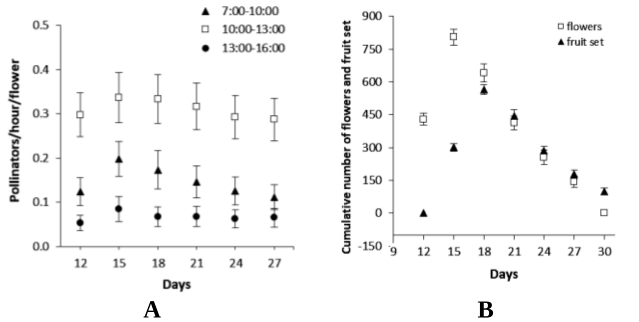


Figure 3. Pollinators' visitation rate. A. Pollinators visitation rate on citrus flowers; B. The number of flowers and fruit sets of *C. reticulata* var. *RGL*

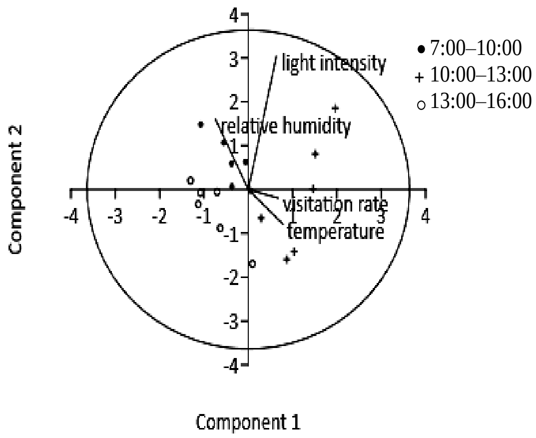


Figure 4. Principal component analysis (PCA) between the microclimate and with visitation rate of pollinators

Phenological stages, pollination success, and citrus productivity

Many studies have shown that plants will change their growth and phenology under different agricultural ecosystems (Campbell et al. 2013; Tschoeke et al. 2015; Gallagher and Campbell 2020). The phenological stage of citrus varies according to the species and variety (Shafqat et al. 2021). Phenological stages of citrus were observed, with five days required for the stages from bud break to petal elongation (P-value <0.05) (Figure 5). Subsequently, two days were needed to transition to the pre-bloom stage (P-value <0.05). The stages from pre-bloom to full bloom took two days (P-value < 0.05). Three days after full bloom, fruit set occurred (P-value <0.05), with mature fruits ready for harvesting after 227 days (P-value <0.05). *Citrus reticulata* var. *RGL* began flowering in December, similar to *C. reticulata* var. Blanco typically flowers between December and January (Jhade et al. 2018; Shafqat et al. 2021). The period from bud break to full bloom spanned 10 days, similar to other citrus varieties, which require around 10-15 days (Reykande et al. 2013). Fruits from *C. reticulata* var. RGL matured after 240 days, comparable to *C. reticulata* var. Blanco matures after 240-260 days (Jhade et al. 2018), and other varieties take 260-275 days (Reykande et al. 2013).

The number of flowers among the three treatments did not significantly differ (P >0.05) (Table 2). However, the number of fruit sets was lower for wind pollination compared to open pollination and *T. laeviceps* (P-value <0.05). Calculated pollination success indicated that open pollination and *T. laeviceps* exhibited the highest rates (P-value >0.05), while wind pollination yielded the lowest (P-value <0.05). The results confirm that the fruit set is higher in the open than in wind pollination (Putra et al. 2014; Azmi et al. 2017, 2019). *T. laeviceps* as a pollinator resulted in a fruit set equal to open pollination, while wind pollination produced a lower fruit set. This suggests that *T. laeviceps* could replace wild pollinators with similar fruit set if the wild pollinator population declines, as previous studies have shown a 30-40% reduction in fruit set when wild pollinators are absent (Siregar et al. 2016; Layek et al. 2021) and the mature fruits decreased by 30-40% (Jhade et al. 2018; Shafqat et al. 2021). This happens because many factors influence the natural phenomenon of all fruit plants.

The development of the number of fruits set each month was observed until they became harvested fruit (Figure 6.A). The number of fruit sets that became the fruits of all treatments has a robust positive correlation (r = 0.48, P-value = 0.03). The number of fruits by wind pollination is lowest compared to open pollination and *T. laeviceps* (P-value >0.05) (Figure 6.B). The fruit weight of citrus from wind pollination is the lowest compared to other treatments (P-value >0.05) (Figure 6.C). This difference makes the estimated productivity of wind pollination produce as the lowest (P-value >0.05). This study shows that resulting fruit weight and estimated productivity have a strong positive correlation (r = 0.76, P-value = 0.02). Following many previous studies, open pollination and *T. laeviceps* produced the highest citrus fruit weights than wind pollination (Nicodemo et al. 2013; Silva et al. 2013; Azmi et al. 2019; Hall et al. 2020). Furthermore, the estimated productivity of open pollination was 4.28 tons/ha/year, while *T. laeviceps* pollination resulted in 4.17 tons/ha/year, and wind pollination yielded 2.82 tons/ha. The average productivity of *C. reticulata* var. *RGL*, after five years, is expected to reach 5 tons/ha/year (Indonesian Citrus and Subtropical Fruits Research Institute 2019).

Table 2. Effects of pollination method on fruit set of citrus plant

Treatment	Number of flowers per plant	Number of fruit set per plant	Fruit set (%)
Wind pollination	156.25 ± 2.41a	80.25 ± 0.96b	51.38 ± 1.08b
Open pollination	154.75 ± 3.10a	111.75 ± 1.71a	72.22 ± 0.57a
T. laeviceps	153.50 ± 3.11a	110.50 ± 2.35a	71.99 ± 0.51a

Notes: Data are means ± SD. Different letters within a column indicate treatment differences at P < 0.05 (*N* = 4)

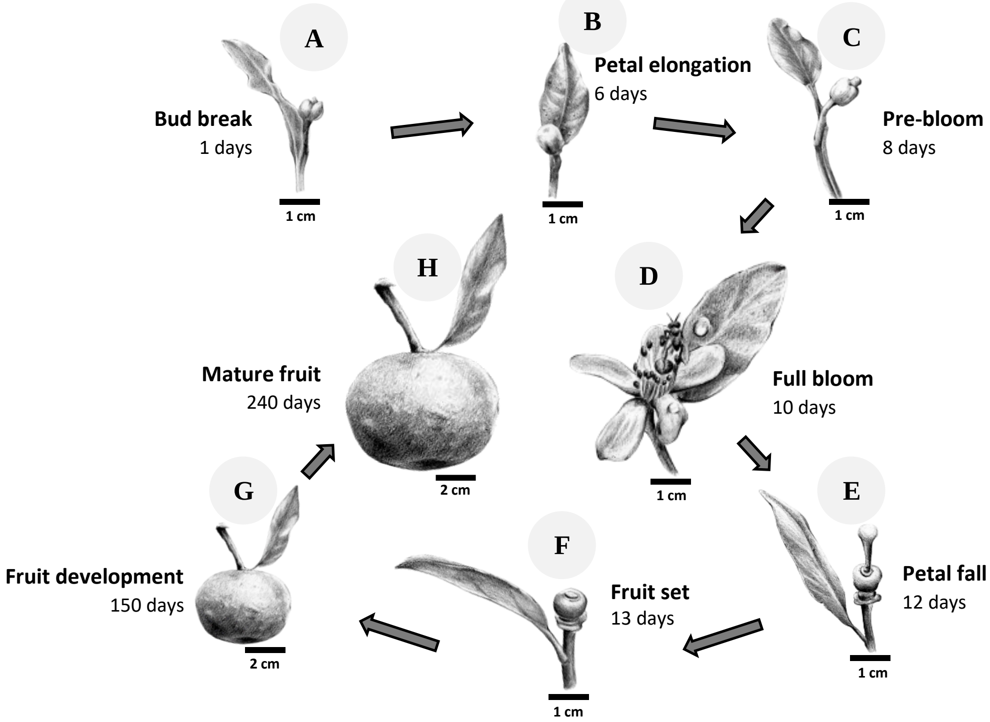
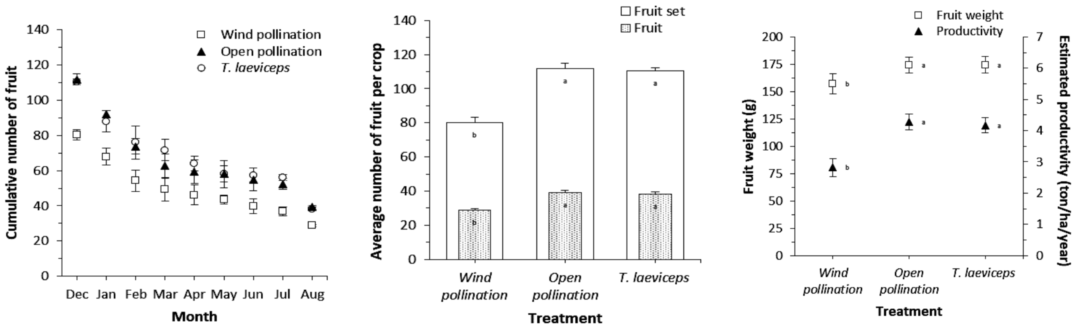


Figure 5. Botanical art of phenological stages for *Citrus reticulata* var. *Rimau Gerga Lebong*



A B C

Figure 6. Fruit set and estimated productivity of citrus. A. The citrus fruit drop pattern; B. Comparison of fruit set with fruit; C. The fruit weight and estimated productivity of citrus with open, wind, and *T. laeviceps* treatments. Different letters within a column indicate treatment differences at P <0.05 (*N* = 4)

Meliponiculture *T. laeviceps*, as pollinators for citrus plants, has demonstrated a high level of adaptation and has become the most abundant pollinator species. Importantly, this cultivation of *T. laeviceps* did not negatively impact the diversity of wild pollinators. The study identified that the peak visitation rate of pollinators to citrus flowers occurred between 10:00 and 13:00, and this visitation rate was influenced by microclimate conditions such as temperature, relative humidity, and light intensity. The phenological stages of *Citrus reticulata* var. *Rimau Gerga Lebong* from bud break to mature fruit took approximately 240 days. Fruit set, fruit weight, and estimated productivity of citrus were higher in *T. laeviceps* and open pollination than in wind pollination. This study suggests that *T. laeviceps* can be successfully cultivated and employed as an effective pollinator for citrus plants, contributing to increased fruit set and overall productivity in citrus orchards. This research provides valuable insights into sustainable pollination strategies for citrus cultivation, particularly in regions facing declining pollinator populations by employing the meliponiculture stingless bee.

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