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Local factors dominantly influence citrus red mite (*Panonychus citri* (McGregor)) population over landscape factors in Indonesian citrus orchards

Faktor lokal lebih dominan mempengaruhi populasi tungau merah jeruk (*Panonychus citri* (McGregor)) daripada faktor lanskap pada pertanaman jeruk di Indonesia

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ABSTRACT

The citrus red mite *Panonychus citri* (McGregor) is a major pest that can reduce the quality and yield of citrus crops. However, information regarding the local and landscape factors that influence its population dynamics remains limited. This study aimed to analyse the influence of local and landscape factors on citrus red mite population density. The research was conducted in nine citrus orchards in Malang, East Java, Indonesia. Data collected included local factors (pesticide application frequency and plant canopy density) and landscape factors (landscape composition, encompassing the number of patches (NP) and class area (CA) of semi-natural habitats). Pesticide application frequency data were obtained through farmer interviews, while canopy density was measured using a photographic method and analysed with ImageJ2 software. Landscape composition data were by digitizing land-use types within a 500-meter radius of the plot center using QGIS software and subsequently analysed using LecoS (QGIS add-ins) to obtain the NP and CA of semi-natural habitats. The generalized linear model (GLM) analysis indicated no overall significant influence of both local and landscape factors on *P. citri* population density. However, it was found that the variation in mite population density was significantly influenced by citrus plant canopy density. These findings suggest that local factors, particularly the canopy microhabitat conditions, are more critical in affecting the *P. citri* population compared to landscape factors. Therefore, the management strategy for citrus red mite should be focused on the local, on-farm scale.

Key words: canopy density, landscape composition, pest management, population density, spatial variation

ABSTRAK

Tungau merah jeruk *Panonychus citri* (McGregor) merupakan salah satu hama penting yang dapat menurunkan kualitas dan hasil panen jeruk. Namun, informasi mengenai faktor-faktor yang memengaruhi populasinya pada skala lokal dan lanskap masih terbatas. Penelitian ini bertujuan untuk menganalisis pengaruh faktor lokal dan lanskap terhadap kepadatan populasi tungau merah jeruk. Penelitian dilakukan pada sembilan pertanaman jeruk di Malang, Jawa Timur, Indonesia. Data yang dikumpulkan meliputi faktor lokal (frekuensi aplikasi pestisida dan kerapatan kanopi tanaman) dan faktor lanskap (komposisi lanskap meliputi *number of patch* (NP) dan *class area* (CA) habitat semi-alami). Data frekuensi aplikasi pestisida diperoleh melalui wawancara dengan petani, sedangkan kerapatan kanopi diukur menggunakan metode fotografi lalu dianalisis menggunakan perangkat lunak ImageJ2. Data komposisi lanskap diperoleh melalui digitasi tipe penggunaan lahan dalam radius 500 m dari pusat plot menggunakan perangkat lunak QGIS dan kemudian dianalisis menggunakan LecoS (ekstensi QGIS) untuk memperoleh NP dan CA habitat semi-alami. Analisis *generalized linear model* (GLM) menunjukkan bahwa tidak ada pengaruh signifikan dari faktor lokal dan lanskap terhadap kepadatan populasi *P. citri*. Namun, variasi kepadatan populasi tungau dipengaruhi oleh kanopi tanaman jeruk. Temuan ini menunjukkan bahwa faktor lokal, khususnya kondisi mikrohabitat kerapatan kanopi, lebih penting dalam mempengaruhi populasi *P. citri* dibandingkan dengan faktor lanskap. Oleh karena itu, pengelolaan hama tungau merah jeruk sebaiknya difokuskan pada skala lokal di tingkat pertanaman.

Kata kunci: kerapatan kanopi, kepadatan populasi, komposisi lanskap, pengelolaan hama, variasi spasial

INTRODUCTION

Citrus crops are of significant economic value in Indonesia, with production reaching 2.8 million tons in 2023, primarily led by East Java (Central Bureau of Statistics of Indonesia 2024). Citrus orchards not only provide substantial benefits to farmers but also bolster both local and national markets (Lv et al. 2015; Hidayat et al. 2022). Despite this importance, production is frequently threatened by pests and diseases. These biological threats attack plants from flowering to harvest, leading to heavy losses and significantly reducing fruit quality (Kilcher 2005; Abobatta 2018). For instance, recent study in Langkat, North Sumatra, have identified 16 insect families as major pests in citrus orchards (Kurniawan & Siregar 2023).

Mites pose a significant threat to citrus production, potentially reducing fruit yields by as much as 70% by cause brown skin discoloration, rough skin, and stunted fruit growth (Ebrahim & Aiad 2019; Wicaksono et al. 2022). Specifically, the citrus red mite *Panonychus citri* (McGregor) (Tetranychidae) is a polyphagous species known to infest various food crops, trees, and ornamental plants (Hoy 2011). *P. citri* is recognized as a major economic pest in citrus orchards globally, including regions across Asia, the Mediterranean Basin, North America, South America, and Africa (Urbaneja et al. 2020). Due to its adaptability, this mite can infest virtually all citrus varieties and species.

Severe *P. citri* infestations primarily impact citrus productivity and quality. The direct feeding damage prevents normal fruit development, leading to fruit drop, although remaining fruits may partially compensate by gaining weight, the overall effect is still a significant (~10%) reduction in yield (Faez et al. 2018). Physiologically, mites damage the plant by sucking cytoplasm from plant cells, which causes chlorotic (yellow) spots and can trigger premature leaf fall (Demard & Qureshi 2022). This loss of cytoplasmic contents reduces chlorophyll levels and photosynthesis, further impairing tree health and potentially degrading fruit quality (Afzal et al. 2023; Assouguem et al. 2024). Beyond agronomic losses, *P. citri* imposes substantial economic burdens. Infestation necessitates increased production costs, primarily through the need for more frequent acaricide applications and the implementation of integrated pest management (IPM) strategies. Furthermore, the external defects and poor quality resulting from major infestations severely reduce the marketability of fruits, negatively affecting both domestic and international commercial sectors (Faez et al. 2018; Radonjić & Hrnčić 2020).

To develop effective and sustainable control strategies for mites, it is essential to study their density and distribution in citrus orchards, requiring and integrated understanding of both local (field) and landscape factors (Rizali et al. 2024). Local factors, such as canopy density and pesticide application, directly influence pests and natural enemy presence. Canopy density affects the light penetration, which in turn dictates crucial microclimatic conditions like temperature and humidity (Devi & Challa 2019; Zhang et al. 2019). The significance of temperature is evident since *P. citri* can complete its life cycle in approximately one week at 25 °C, and its population often peaks during favourable temperatures periods in early spring or fall (Zhang 2003; Demard & Qureshi 2023). Conversely, non-optimal temperatures and humidity levels typically lead to a decline in arthropod populations (Shrestha 2019). Furthermore, frequent pesticide applications disrupts natural biological systems, induces pest resistance, and can ultimately lead to a resurgence or increase in pest population over time (Rattanpal et al. 2017; Urbaneja et al. 2020; Afzal et al. 2023; Demard et al. 2024).

Landscape factors, particularly landscape composition, also play a crucial role by influencing fauna diversity and population density. Croplands situated near natural habitats generally exhibit greater natural enemy diversity and species richness (Pasaribu et al. 2024), while complex landscapes support more abundant and diverse natural enemies that indirectly regulate pest populations (Martin et al. 2016). For example, the presence of natural habitats within oil palm plantations affects the species richness and abundance of natural enemies (Rizali et al. 2024). Similarly, semi-natural habitats can acts as dispersal or refuge sites for predatory mites (Phytoseiidae) in vineyards, suggesting that the lack of such habitats may contribute to a decrease in their population (Möth et al. 2023).

While numerous studies have thoroughly examined the basic biology and ecology of *P. citri* (e.g., Kasap 2009; Zanardi et al. 2015; Demard & Qureshi 2022), research focusing on how local and landscape factors concurrently influence its population density and spatial variation in citrus orchards remains limited. Most existing research has highlighted the direct effects of pesticides on mites (Amiri-Besheli et al. 2020), but rarely incorporates landscape variables, such as landscape composition, into integrated mite management strategies (Möth et al. 2023). Specifically, studies investigating how the interplay of factors like canopy density, pesticide application, and landscape composition, collectively shape *P. citri* population are scarce. Therefore, this study aimed to investigate the effects of local factors (i.e., frequency of pesticide application and canopy density) and landscape factors (i.e., landscape composition) on the population density and spatial variation of *P. citri* in Indonesian citrus orchards.

MATERIALS AND METHODS

Study area and plot design

This study was conducted in nine citrus orchards across three districts: Dau, Bumiaji, and Poncokusumo, in Malang, East Java, Indonesia. The orchards were selected based on criteria adapted from Wicaksono et al. (2022), ensuring all sites had producing citrus trees aged of 2–7 years, a minimum area of 1,200 m^2, and were separated by a distance at least 1 km but no more than 20 km. These nine orchards were distributed across nine villages (Figure 1A), with elevations ranging from 578 to 994 m above sea level. The region features a tropical wet climate, with an average air temperature of 26.25 °C and relative humidity of 75.5% (Meteorology, Climatology, and Geophysical Agency 2024). All orchards cultivated the same citrus variety, *Citrus nobilis* L., at an average planting distance was 3 m × 3 m. Furthermore, farm management practices were consistent across sites: farmers used mixed fertilizers (organic and inorganic), applied chemical pesticides, and performed annual pruning (typically one to three times per year).

For the purpose of the study, a 900 m^2 (30 m × 30 m) plot consisting of 81 plants was established in each orchard (Figure 1B). This central placement was chosen to minimize border and edge effects and covered approximately 75% of the area of the smallest selected orchards.

Local factor data collection

Local or field data collection focused on pesticide application frequency and citrus canopy cover. Data on pesticide application frequency, types, and methods were gathered through interviews with the citrus orchard owners. The owners reported an average application frequency of one to four times per month. The pesticides used, including fungicides, insecticides, and acaricides, were consistently applied by direct spraying. Citrus canopy cover (canopy density) was measured using a photographic method. In each

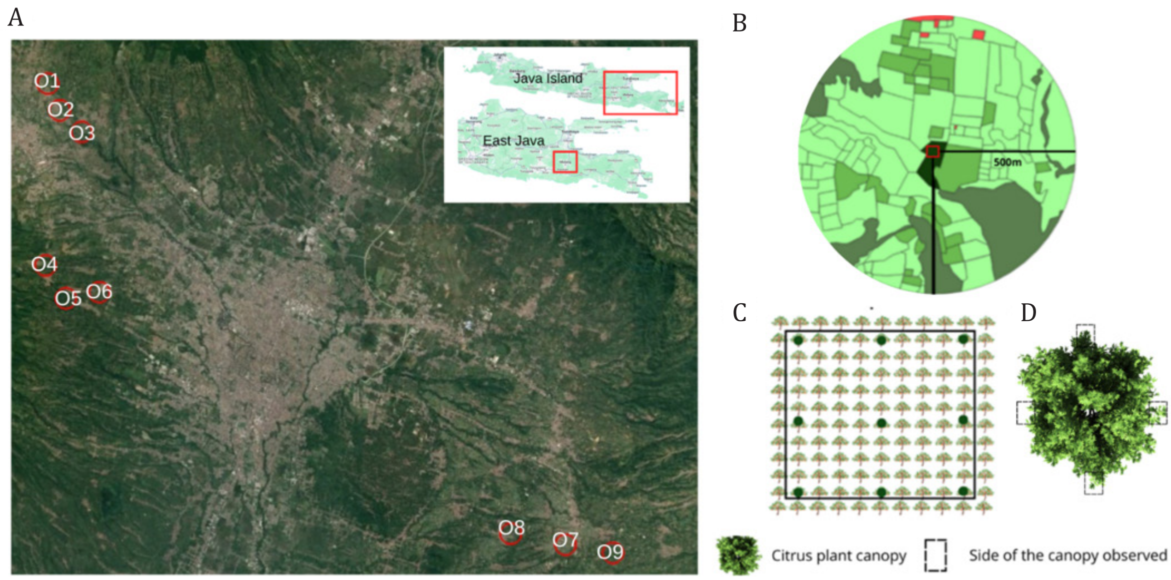

Figure 1. A: Study area research citrus orchards in Malang, East Java, Indonesia. O1: Bulukerto; O2: Bumiaji; O3: Pandanrejo; O4: Gadingkulon; O5: Tegalweru; O6: Selorejo; O7: Karangnongko; O8: Wonorejo; O9: Ngebruk. B: results of landscape digitization in one of the study orchards; C: observation plots; D: layout of the four sample leaves (view from above) in the canopy of each sample citrus plant.

orchard, five representative locations were selected, with each point representing a subplot of four citrus trees. Photographs were taken from the ground toward the canopy using a camera positioned 30 cm above the ground. The resulting images were subsequently processed using ImageJ2 software to determine the percentage of canopy density. This value was calculated as the average of the measurements taken at the five photographic points (Rueden et al. 2017; Muhammad et al. 2022).

Landscape characterization

We characterized the landscape surrounding each citrus orchard within a 500 m radius. This radius was selected based on previous studies indicating its suitability for observing interactions between arthropods and their habitats, as it often encompasses the relevant spatial range for natural enemies and other arthropods (Möth et al. 2023; Pasaribu et al. 2024). Landscape characterization was performed using ground checks with Google Earth as the base map. We recorded land use types and classified them into six distinct categories: (i) semi-natural habitats: areas with natural characteristics and minimal human intervention, including secondary forests, savannas, and grasslands (Guo et al. 2022), (ii) citrus orchards: commercial or small-scale plantations of citrus trees (*Citrus* spp.) (Pilon et al. 2023), (iii) annual cropland: areas planted with annual crops, such as vegetables, at least once within a 12-month period (Defourny et al. 2014), (iv) farms: places where livestock are bred and raised for ecological benefit, (v) open areas: areas without vegetation cover, and (vi) settlements: areas used for human habitats, including towns and villages (Harrison 2006) (Figure 2). Each landscape within the defined radius was digitized using QGIS software (QGIS Development Team 2024). We analysed the landscape composition using the Landscape Ecology Statistics (LecoS) plugin (Jung 2013) to obtain two key landscape parameters for each land use type: class area (CA), defined as the area (in hectares) of a particular habitat category, and the number of patches (NP) of semi-natural habitats.

Sampling of mites

To capture seasonal variations in population density, *P. citri* sampling was conducted twice: in the first week of November 2023 and the first week of December 2023. Both sampling events were performed either before or after pesticide application. We consistently sampled young leaves, as *P. citri* shows a clear preference for them. To account for potential microclimatic differences within the canopy (Puspitarini & Endarto 2021; Qureshi et al. 2021). We collected four leaf samples from each sample tree at an approximate height of 2 m above ground level, one leaf from each cardinal direction (east, north, west, and south). In total, 36 citrus leaves were collected from the sample plants in each orchard. All leaves were carefully cut and placed in labelled plastic bags to prevent mite loss during transport. The bags were then stored in an ice box and refrigerated to keep the leaves fresh and immobilize the mites before counting.

The mite population was counted immediately upon return using a stereomicroscope. To prepare for identification, slides were created from the collected samples. After two to three days, when the mite bodies were clearly visible, identification was performed using a compound microscope. Mites were identified by examining their morphology to confirm they matched *P. citri*, as described in Zhang's book Mites of Greenhouses: Identification, Biology, and Control. Finally, the average and coefficient of variation (CV) of *P. citri* per orchard were calculated.

Data analysis

We analysed the effects of landscape composition and local factors on the mean population density and spatial variation of *P. citri*. The mean population density and the spatial variation, represented by the coefficient of variation (CV), were calculated for *P. citri* per orchard. To model the relationship, we used a generalized linear model (GLM) without interaction terms. A quasi-Poisson distribution was employed to account for potential overdispersion in the count data (Bolker et al. 2009; Zuur et al. 2009). The explanatory variables included both landscape and local factors: (i) landscape factors: class area (*CA.nat*) and number of patches (*NP.nat*) of semi-natural habitats, and (ii) local factors: frequency of pesticide application and percentage of canopy cover (canopy density). To prevent multicollinearity issues, all explanatory variables were checked for correlation using the variance inflation factor (VIF) test. All statistical analyses were conducted using R statistical software (R Core Team 2024).

RESULT

Population density and spatial variation of *P. citri* in citrus orchards

The observed *P. citri* population density varied across the surveyed citrus orchards, ranging from 6.25 to 13.27 mites per four leaves sampled from a tree (Figure 3). Significant spatial variation in population density was also evident among the trees within each plot (Figure 3). Based on the coefficient of variation (CV), the population density in Pandanrejo Village exhibited the highest spatial variation (CV = 49.62%). This finding indicates a highly heterogeneous distribution of the *P. citri* population among the trees in that orchard compared to others. Conversely, the population density in Bulukerto Village was the most homogeneous (CV = 29.08%), suggesting a relatively even distribution of mites among the trees.

Effect of local and landscape on *P. citri* population density in citrus orchards

We hypothesized that both local factors (pesticide application and canopy cover) and landscape composition would influence the population density of citrus mites in the orchards. Landscape characterization revealed that all nine study orchards included semi-natural habitats, though the proportion varied across sites (Figure 2; Table 1). Based on the LecoS analysis, the key landscape factors, the number of patches (NP) and class area (CA) of semi-natural habitats, ranged from 2–15 patches and 1.50–16.65 ha, respectively (Table 1). Local factors also exhibited high variation. The frequency of pesticide application across the study sites ranged from one to four times per month (Table 1). Similarly, canopy cover (canopy density) varied substantially, ranging from a minimum of 6% in Karangnongko to a maximum of 83% in Bumiaji (Table 1).

The generalized linear model (GLM) analysis showed that neither the landscape factors (*NP.nat* and *CA.nat*) nor the local factors (pesticide application frequency and canopy density) significantly affected the mean density of the *P. citri* population (Table 2, P

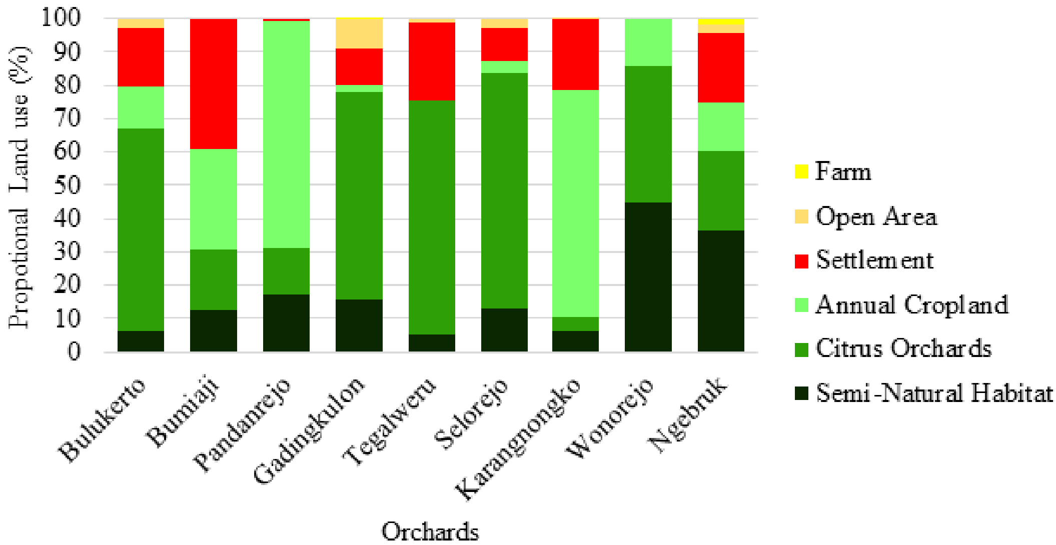

Figure 2. Landscape composition in the study area.

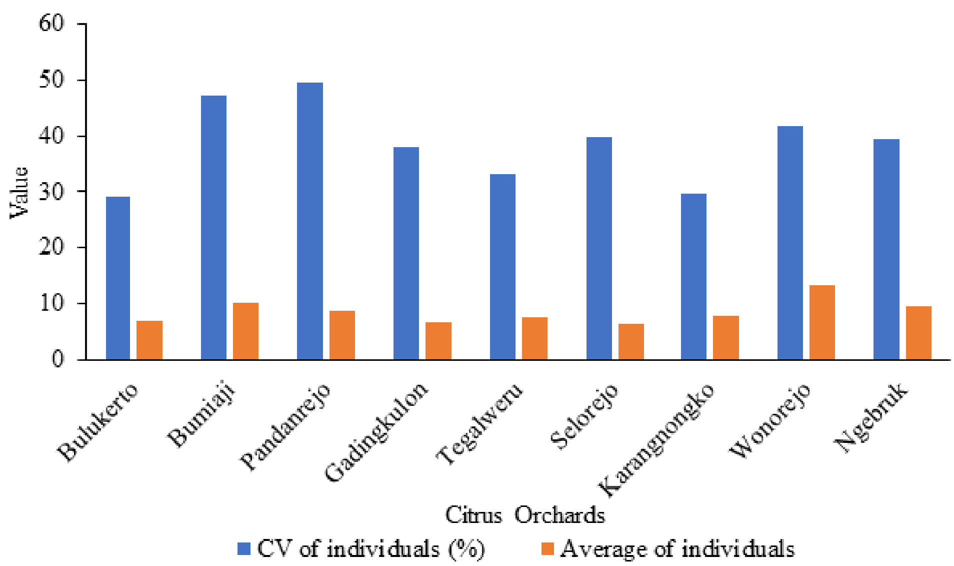

Figure 3. Average of spatial variation (CV) and average population density (per four leaves sampled tree) of *Panonychus citri* from 2 sampling in citrus orchards.

> 0.05). This suggests that variations in both landscape composition and these local management practices do not significantly influence the mean *P. citri* density. In contrast to population density, the GLM analysis revealed that a local factor, canopy density, had a significant positive effect on the spatial variation of the *P. citri* population (Table 2, P = 0.039). This result indicates that increased canopy density leads to greater spatial variation (heterogeneity) in the *P. citri* population within citrus orchards. Conversely, the analysis found that the landscape factors (*NP.nat* and *CA.nat*) did not influence the spatial variation of the *P. citri* population (Table 2, P > 0.05).

DISCUSSION

Our study demonstrated that local factors, particularly canopy density, exert a stronger influence on the spatial variation of *P. citri* populations than do landscape factors. Crucially, we found that neither local nor landscape factors significantly influenced the average population densities of the mites. The positive effect of canopy density on the spatial variation of *P. citri* suggests that denser canopies promote a heterogeneous (uneven) distribution of the mite population within an orchard. A higher coefficient of variation (CV) value confirms this greater unevenness in the mite's spread between trees (Asriyanti 2013). This heterogeneity is likely driven by two key mechanisms facilitated by dense canopies: enhanced dispersal and aggregation and microclimate regulation. Connected canopies facilitate physical contact between leaves and branches, which is the primary mode of *P. citri* spread (Vashisth et al. 2021). This movement, whether by walking, wind currents, or human activity, allows mites to rapidly aggregate in specific microhabitats that favour survival and reproduction. When the canopy is closed, mites tend to gather in such optimal spots, thereby increasing the unevenness of their distribution. In contrast, open canopies may lead to a more even spread or present physical barriers due to gaps between trees (Mockford et al. 2024).

Canopy density significantly affects the microclimate by controlling sunlight exposure, which in turn influences temperature, humidity, and light (Devi & Challa 2019; Zhang et al. 2019; Abobatta 2020). Dense canopies maintain higher humidity, which prevents mite eggs and larvae from desiccating, and keep temperatures within the optimal 15–35 °C range that supports *P. citri* development (Dong et al. 2020). Open canopies, by allowing more sunlight and air circulation,

Table 1. Landscape and local factors in citrus orchards in Malang: number of patches (NP.nat) and class area (CA.nat) of semi-natural habitat, frequency of pesticide application (FPA), and canopy density (%)

Orchards	Landscape factors		Local factors	
	CA. nat (ha)	NP. nat	FPA (times/ month)	Canopy density (%)
Bulukerto	4.91	4	2	12.41
Bumiaji	13.44	15	4	83.16
Pandanrejo	9.78	6	4	68.43
Gadingkulon	4.58	2	2	14.49
Tegalweru	1.50	6	2	60.43
Selorejo	3.39	2	2	55.24
Karangnongko	12.25	3	2	6.15
Wonorejo	16.65	6	3	53.38
Ngebruk	4.32	2	1	27.22

Table 2. Generalized linear models (GLM) showing the relationship between the population density of *Panonychus citri* and the following variables: number of patches (NP.nat) and class area (CA.nat) of semi-natural habitat, frequency of pesticide application (FPA), and canopy density (%)

Variable	Mean of individuals			CV of individuals		
	Est	SE	P	Est	SE	P
intercept	1.704	0.15	<0.001	-1.263	0.17	<0.001
NP.nat	0.025	0.02	0.291	-0.055	0.09	0.554
CA.nat	0.005	0.00	0.495	0.014	0.02	0.602
FPA	0.088	0.08	0.308	0.006	0.00	0.505
Canopy density	0.000	0.00	0.946	0.006	0.00	0.039*

*: P < 0.05; Est: Estimate; SE: Std. Error; P: P value.

create drier conditions that can increase mite mortality rates (Zhang et al. 2019). Furthermore, dense canopies may offer complex habitats and protection for natural enemies, potentially increasing their survival and hunting efficiency (Prischmann et al. 2006; Abobatta 2020), which further contributes to localized mite suppression and, consequently, spatial variation.

Our finding that pesticide use did not affect the population density or spatial variation of *P. citri* mites suggests that the mite population remained relatively stable despite varying application frequencies. Based on farmer interviews, this lack of efficacy may be attributed to inappropriate application practices, such as mixing incompatible pesticides (e.g., fungicides and insecticides). Such misuse can reduce the effectiveness of the active ingredients and accelerate pest resistance (Asaad 2008; Rahmasari & Musfirah 2020). This highlights a critical lack of proper pesticide knowledge among local farmers. Promoting the correct use of pesticides (right target, quality, type, dose, time, and method) and encouraging the adoption of eco-friendly alternatives, such as black soap and detergent mixes (Amiri-Besheli et al. 2020; Assouguem et al. 2023), are necessary steps to achieve effective pest control.

Although complex landscapes are generally expected to boost natural enemies and plant diversity, thereby affecting pest populations (Syahidah et al. 2021; Zuhran et al. 2021; Rizali et al. 2024), the GLM analysis in this study found that landscape composition (number of patches and class area of semi-natural habitats) did not influence *P. citri* density or spatial variation. This suggests that the spread of *P. citri* is likely limited to the immediate local environment. While mites can spread by walking, human assistance, and wind ("ballooning") (Demard & Qureshi 2022; Tehri 2014), this airborne dispersal method is generally considered limited to short distances (Montes & Glieser (2025). The short-term nature of this movement may prevent a strong landscape factors effect on the overall population or its spatial arrangement. Additionally, the inherent biological traits of *P. citri*, including its short life cycle, high reproductive rate, adaptability, and ability to utilize resources in its current habitat, may override any mitigating effects offered by surrounding landscape heterogeneity (Zhang 2003; Tscharntke et al. 2016; Devi & Challa 2019; Qureshi et al. 2021).

CONCLUSION

Our study revealed that the population of *P. citri* varied in both density and spatial distribution among the citrus orchards. We found that, in general, neither local nor landscape factors significantly influenced the mites' overall population size. However, a key finding was that canopy density at the local level significantly influenced the spatial variation of *P. citri*, while pesticide use did not. This indicates that local conditions, specifically canopy proximity, are more important than broader landscape factors in determining how mites are distributed within an orchard. Consequently, effective *P. citri* management should focus on local factors. For instance, strategically pruning trees to create a more open canopy can alter the microclimate, making the habitat less favourable for mites while simultaneously benefiting natural predators that help control the population.

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