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Environmental and agronomic factors affecting mealybug populations in papaya

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ABSTRACT

Mealybug infestations are a growing concern in tropical horticulture due to their rapid population increase and the significant damage they cause to fruit crops. This research examined the severity of attack and population density of mealybugs (Pseudococcidae) on papaya (*Carica papaya* L.), and analysed their relationship with environmental conditions and cultivation practices in several locations in Tarakan City, North Borneo. The study was conducted from January to April 2025 at seven papaya cultivation sites, including Juata Laut 1–5, Juata Permai, and Karang Harapan. A field survey combined with purposive sampling was applied to assess a minimum of 100 papaya trees over one year old at each site. Data collected included the number of infested trees, mealybug population per plant, types of fertilizers and pesticides used, plant age, and surrounding land conditions. The percentage of trees infested with mealybugs ranged from 25.07% to 38.89%, while the average mealybug population on infested trees ranged from 199.52 to 224.59 individuals per plant. Sites characterized by intensive application of chemical fertilizers and pesticides—such as Juata Laut 2 and Juata Laut 4—showed higher infestation levels than those managed with organic practices, such as Juata Permai. Environmental factors, particularly high humidity and inadequate drainage, were also associated with increased mealybug population growth. These findings indicate that environmental conditions and cultivation techniques play a substantial role in shaping the population dynamics of mealybugs. The results highlight the importance of implementing Integrated Pest Management (IPM) strategies that emphasise ecological approaches and environmentally sustainable cultivation practices to mitigate mealybug infestations in humid tropical regions such as Tarakan City.

Keywords: *Carica papaya*; Cultivation practices; Environmental factors; Pest population dynamics; Tarakan City; Mealybug infestation

1. Introduction

Tarakan City in North Borneo has been known for its substantial potential for horticultural cultivation, including the California papaya (*Carica papaya* L.). This variety has been widely chosen because it is more economically valuable than local varieties (Sibuan et al., 2024). It has a sweeter taste, thicker flesh, and a longer shelf life. Papaya is also rich in vitamin C, vitamin A, and the enzyme papain. As a corollary, it has gained its popularity as a multifunctional commodity for both fresh consumption and industrial raw material (Saeed et al., 2014).

Tarakan City's Central Statistics Agency (BPS) further reported that papaya production has been on the rise and labelled papaya as a strategic horticultural commodity for both local consumption and beyond. Nevertheless, successful cultivation is often obstructed by Plant Pest Organisms (PPO). One of the most problematic pests is the mealybug, a member of the order Hemiptera, family Pseudococcidae.

The sucking action of mealybugs on papaya can reduce fruit quality, as indicated by blackening or wrinkling of the surface, and contribute to yield reduction and the death of juvenile plants (Amelia, 2021). Amelia (2021) also reported that mealybug attacks can increase production costs by up to 84% and reduce yields by up to 58%. This makes it a serious threat to the sustainability of papaya farming businesses. Previous studies have documented that various environmental factors, such as temperature, humidity, rainfall, and light intensity, affect mealybug populations, and so do such agronomic factors as plant density, planting patterns, and pesticide use (Mwanauta et al., 2022).

Some other studies have documented that humid tropical environments like those in Tarakan are highly conducive to mealybug development. Species, like *Paracoccus marginatus*, thrive at a minimum temperature of 14.7 °C, develop optimally at 28 °C, and produce 300–500 eggs per female in a single reproductive cycle. Under suitable environmental conditions, populations can develop in two to four generations per year (Subramanian et al., 2021). This is in line with Ahmed et al. (2015), who reported that *P. marginatus* has emerged as an invasive species with decent adaptability to a wide range of tropical agroecosystem circumstances.

In addition to environmental factors, cultivation practices have a bearing on mealybug population. In this regard, plant spacing, high watering frequency, and excessive nitrogen fertilization can accelerate pest population growth by creating humid microclimates and abundant food sources (Rizwan et al., 2022). Conversely, good cultivation systems such as crop rotation, garden sanitation, and the use of organic materials can suppress pest populations (Sarma et al., 2024).

Although mealybugs are known to attack various horticultural crops in Indonesia, studies on the relationship between environmental factors and cultivation techniques on mealybug populations on papaya in Tarakan City are underexplored. This void underlines the urgency for further inquiry to gain a fine-cut understanding of the factors influencing pest population. Such an investigation lends itself to designing an ecologically-based integrated pest management strategy for papaya farming in tropical regions.

2. Materials and Methods

2.1. Time and Site of the Research

This research was conducted from January to April 2025, taking place at seven papaya cultivation sites in Tarakan City, North Borneo. Five locations are in Juata Laut subdistrict, one location is in Juata Permai subdistrict and one location is in Karang Harapan subdistrict. Involving diverse sites was aimed at documenting diverse environmental conditions and papaya cultivation systems. Subsequent mealybug population was enumerated at the Plant Protection Laboratory, Faculty of Agriculture, University of Borneo Tarakan.

2.2. Research Design

Engaging a quantitative descriptive method through a field survey, this research sought to capture the environmental and agronomic practices affecting the population of mealybug (Hemiptera: Pseudococcidae) on papaya plants at various cultivation sites. This design allowed the observation of the dynamics of a natural population without experimental treatment.

2.3. Sampling Technique

The researchers took the following criteria into account upon sampling:

1. The site had at least 100 papaya trees.
2. The plants were at least 1 year old to ensure stable and representative planting conditions.
3. The farmers agreed to provide information about cultivation practices and land management.

The observations at these seven sites were conducted on the same day, involving a maximum of five trees per location. In total, 35 trees were observed per day. At each site, observations were carried out until all papaya trees present at that location had been fully examined. The trees observed each day were different from those examined on previous days, ensuring that each tree was surveyed only once during the entire study period. Mealybugs were collected using a fine brush and stored in Eppendorf tubes containing 70% alcohol. These samples were stored for 48 hours to allow the wax layer to degrade entirely. To aid identification, each tube was labelled with the location, collection date, and plant part.

2.4. Observation Parameters

2.4.1. Mealybug Population

The population of mealybugs was enumerated based on the number of individuals found per sample plant at each site. The leaves, stems, and fruit of each observed tree were carefully examined to identify symptoms of mealybug infestation. A tree was categorised as infested if at least one mealybug was detected on any part of the plant. The total number of papaya trees varied across sites; however, each location contained more than 100 trees in total. From these, up to five trees per site were selected for detailed population assessment. This meticulous examination allowed for an accurate quantification of the mealybug population on each sample tree.

The percentage of mealybug-infested trees was calculated for each site to quantify the level of infestation within the local tree population. A tree was classified as infested if at least one mealybug was found on any examined plant part (leaf, stem, or fruit). Although the total number of papaya trees varied among sites, each location contained more than 100 trees.

The infestation percentage was computed using the following formula (1):

$$\text{Infestation percentage (\%)} = \frac{\text{Number of infested trees}}{\text{Total number of trees at the site}} \times 100 \qquad (1)$$

This calculation provided an estimate of the overall proportion of trees affected by mealybugs at each site.

2.4.2. Environmental and Agronomic Factors

The researchers examined several environmental factors, *inter alia,* land conditions, such as drainage, weed presence, and plant spacing. These data were obtained through semi-structured interviews with farmers. It further inquired about the type and dosage of fertilizer administered, the type and amount of pesticide, irrigation system and its frequency, plant age, and garden cleanliness, as well as sanitation.


(a)


(b)

Figure 1. (a) Mealybugs on papaya leaves, (b) the observation of mealybug

3. Results

To illustrate the initial observations made during this study, Figure 1 provides visual evidence of the field and laboratory activities conducted. Figure 1a shows the presence of mealybugs on a papaya leaf as observed directly in the field, serving as confirmation of the infestations encountered during data collection. Figure 1b presents the appearance of the collected specimen under the microscope, further demonstrating that laboratory examination and identification were carried out as part of this research.

As can be appreciated in Figure 2, the infestation percentage ranged from 25.07% to 38.89%, which marked different infestation levels between sites. Another difference between sites is also reported in Figure 3. It reports the average mealybug population on infested papaya trees across sites. The average density of mealybugs per infested tree varied from 199.52 to 224.59 individuals per plant, with an average of 218.86 individuals per plant.

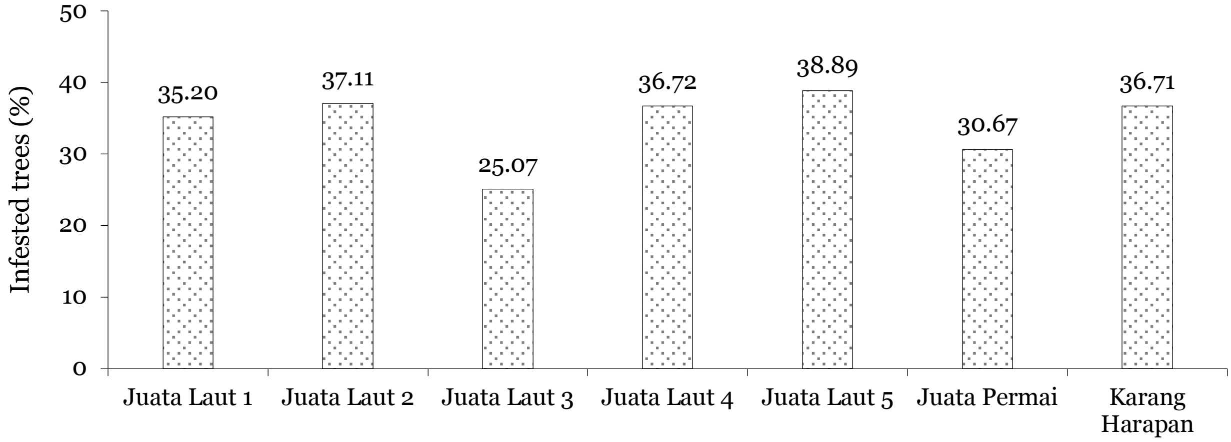

Figure 2. Percentage of infested trees by mealybugs.

The observations revealed diverse patterns of fertilizer and pesticide usage, plant age, and land conditions (Table 1). Most of the participating farmers extensively rely on chemical fertilizers such as urea and NPK, as discovered in Juata Laut 1, Juata Laut 4, and Karang Harapan. Some sites were found to carry out attempts at combining chemical and organic fertilizers, such as chicken manure and NPK, as in Juata Laut 2. This mixture of balanced organic and chemical fertilizers was also evident in Juata Laut 5. Juata Laut 3 relied even more intensively on organic fertilizer from chicken manure, while Juata Permai added cow manure combined with NPK. The data show considerable varieties from 15 to 25 months of papaya plants at the seven sites. Juata Laut 4, with a 15-month-old plant, represents the young phase; Juata Permai, with a 25-month-old plant, represents the mature phase, while the other sites were in the intermediate phase. Pesticide use and land conditions also contributed to these differences. Farmers closer to settlements, such as Juata Laut 1, Juata Laut 4, and Karang Harapan, highly depended on chemical pesticides, in that they administered the pesticides every 10–14 days. This is different from Juata Laut 2 and Juata Laut 3, at which botanical pesticides containing soursop leaf extract were applied only to address imminent infestation. Juata Laut 5 embraced a combination of botanical and chemical pesticides with a lower application interval, every 3 weeks. The most obvious contrast was against Juata Permai, which administered almost no pesticides.

In addition to these practices, the researchers observed different land conditions between sites with poor drainage, such as Juata Laut 4, which was prone to flooding. Several locations were characterized with satisfactory drainage and a natural land profile, such as Juata Permai. Each site was found to be unique. For instance, Juata Laut 3 is situated near a river, which results in a high level of humidity.

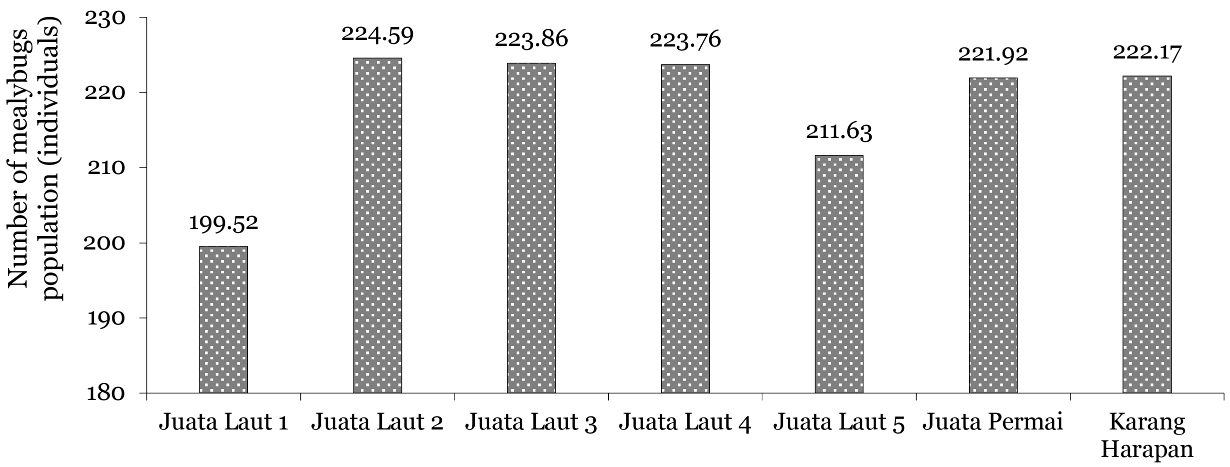

Figure 3. Average mealybugs population on infested papaya trees.

4. Discussion

As indicated by the percentage of infested papaya trees, ranging from 25.07% to 38.89%, this research has revealed significant variation between sites. Another important result was the average mealybug population per infested tree, ranging from 199 to 224 individuals per tree. These trends strongly corroborate the critical roles of environmental factors and cultivation techniques.

Two main components are found to determine the extent of mealybug infestation at the sites. These involve the probability of a tree being infested and the intensity of infestation. The percentage of infested trees reflects the likelihood of infestation in a specific area, and the average mealybug population per infested tree indicates the severity of the infestation on individual plants. The results have affirmed that the percentage of infested trees varied more substantially between sites than did the number of mealybug s per infested tree. The latter was proven fairly consistent at around 200–225 individuals. This shows that environmental conditions and cultivation techniques pose a more acute influence on infestation than on attack intensity.

Juata Laut 2 and Juata Laut 5 recorded the highest infestation rates, at 37.11% and 38.89%, respectively. This is indicated by an average mealybug population of approximately 224 individuals per affected tree. Both sites share commonalities in the intensive fertilization practices and the frequent use of both chemical and botanical pesticides. Juata Laut 2 uses a combination of chicken manure and NPK fertilizers, along with a botanical pesticide based on soursop leaf extract. In contrast, Juata Laut 5 administers organic and chemical fertilizers, in combination with a pesticide mixture applied every three weeks. This is probably owing to the fact that intensive fertilization, coupled with high nitrogen content from NPK fertilizers or fresh organic materials, can enrich nutrients in plant tissues. These generally include nitrogen and carbohydrates, two primary food sources for sap-sucking pests. This result coheres with Rakhesh et al. (2023), noting that high nitrogen content in plant tissues can elevate the attractiveness of plants to mealybugs and accelerate their growth rate. This implies that the absence of a balanced approach to ecosystem management can increase pest populations, albeit with intensified fertilization.

In addition to fertilization, environmental conditions significantly influence mealybug population growth, as evident in Juata Laut 2. This site is located in an open area with good drainage and extensive exposure to direct sunlight. These environmental bearings leverage the temperature around the plants. This is believed to pose a challenge since warm temperatures and high light intensity accelerate the mealybug life cycle. In the same vein, Zhao et al. (2024) argued that temperature and rainfall significantly influence the global distribution of *Paracoccus marginatus*, especially due to high temperatures and low rainfall. This is harmonious with the results from the open and dry conditions in Juata Laut 2, proven an ideal habitat for mealybugs. These results are in contrast to those from Juata Laut 3.

Table 1. Environmental conditions and cultivation techniques.

Site (Subdistrict)	Fertilizer	Pesticide	Plant age (months old)	Land characteristics
Juata Laut 1	Intensive urea and NPK	Chemical pesticides every two weeks	18	Characterized by proximity to residential areas, high humidity, and moderate drainage
Juata Laut 2	Combination of chicken manure and NPK	Plant-based pesticides with soursop leaf extract, applied during pest infestation	20	Characterized by open land, good drainage, and high exposure to direct sunlight
Juata Laut 3	Intensive chicken manure	Plant-based pesticides with soursop leaf extract applied during pest infestation applied during pest infestation	24	Situated close to rivers, with high humidity, often damp during the rainy season
Juata Laut 4	NPK	Chemical pesticides every ten days	15	Characterized by sloping land, poor drainage, and flooding during rain
Juata Laut 5	Combination of organic and chemical	Plant-based and chemical pesticides (every three weeks)	22	Cultivated for mixed papaya and vegetable gardens
Juata Permai	Cow manure and NPK	Almost no pesticide use	25	Having flat natural land, far from residential areas
Karang Harapan	Chemical	Chemical pesticides every two weeks	17	Cultivated for mixed papaya and vegetable gardens

Characterized by its proximity to a river and high humidity, Juata Laut 3 exhibits the lowest infestation rate (25.07%). Humid conditions support several phases of mealybug development, particularly egg and nymph survival. Excessive humidity and frequent rainfall in this circumstance can hinder the spread of the pest colony or the growth of epiphytic fungi. Nevertheless, although maximum and minimum temperatures were positively related to mealybug population density, excessively high humidity suppresses their population (Fanani & Maryana, 2024). This may explain the lowest infestation as discovered in Juata Laut 3.

Another important result was discovered at Juata Laut 4, with its sloping land and poor drainage. This site demonstrated a 36.72% infestation rate. During the rainy season, poor drainage is extensively reported to cause water to pool around plant roots, increasing soil and air humidity around the plant canopy. This environment denotes a thriving arena for sap-sucking insects, while concomitantly undermining the effectiveness of chemical pesticides. At this site, chemical pesticides were applied every 10 days, yet the mealybug population remained high (223 infested individuals per tree). This has proven that excessive use of chemical pesticides can result in reduced effectiveness due to pest resistance and the loss of natural enemy populations. Tanwar et al. (2010) suggests that the prolonged application of synthetic pesticides against *P. marginatus* can resist the population growth of natural parasitoids such as *Acerophagus papayae*.

On the other hand, a relatively low infestation rate of 30.67% and roughly 221 mealybugs per tree were found at Juata Permai, which was managed using cow manure and NPK. This site, characterized by flat land, was distant from settlements and human activities. These features may account for why the use of organic fertilizers sustains micro-ecosystem balance, such as by maintaining the presence of natural predators, such as the *Cryptolaemus montrouzieri* beetle and spiders. A study in East Africa reported that papaya gardens managed without chemical pesticides exhibit lower mealybug infestations than conventional fields (Constantine et al., 2023). In harmony with Kansiime et al. (2023), these results corroborate the importance of integrating biological control in papaya cultivation systems to mitigate pest attacks.

A comparison between Juata Laut 1 and Karang Harapan showed similar results. These are generally identified with attack percentages of 35.20% and 36.71%, respectively. To a large extent, this was believed to result from the common application of chemical pesticides every two weeks at both sites. Additionally, only mealybug populations of approximately 199 and 222 individuals are discovered on each infested tree. One critical point to ponder is that although chemical pesticides help to suppress pest growth, they only temporarily reduce pest population without interrupting their developmental chain. Amelia (2021) even reported that synthetic pesticides may fail to control mealybugs effectively. This is because the insect's body is protected by a thick wax coating from direct contact with synthetic pesticides. This undermines the recommendation for an approach engaging chemical pesticides.

The other determinant for the infestation severity is plant age. The researchers documented plant age ranging from 15 to 25 months. Older plants generally have denser canopies and larger leaf surfaces, providing decent shelter for the pest. Furthermore, older plants are characterized by tougher tissue, which may be less attractive to young nymphs. In this regard, Juata Permai, with a 25-month-old plant, showed moderate infestation, while Juata Laut 4, with a younger plant age of 15 months, exhibited a higher infestation rate. Simply put, the interaction between age, environmental properties, and cultivation strategies denotes a pivotal aggregate of determinants, instead of solely plant age. Moving forward, Chuai et al. (2022) mentioned that the physiological adaptation of *P. marginatus* to the lignification of plant tissue influences the pest's preference for plant age, which accounts for younger plants with softer tissue being more prone to infestation.

The stability of mealybug populations at 200–225 individuals per infested tree across all sites suggests a natural limit to the plant's carrying capacity. Once a population attains a particular density, competition between individuals will bring down plant tissue quality and limit its growth. This is known as density-dependent regulation or population equilibrium. This is in resonance with Biratu (2022), who emphasized that mealybug populations often exhibit a logistic growth pattern, where maximum density is reached immediately before declining due to resource constraints. Therefore, strategies should focus on early prevention to keep the number of infested trees to a minimum, rather than suppressing the population once the attack rate culminates.

The results also capture the influential mechanism of land conditions and other environmental factors. Poorly drained land, such as found in Juata Laut 4, can cause physiological stress in plants due to waterlogging of the roots. Grown in this poor structure, stressed plants will not be able to develop robust defense systems, as indicated by reduced levels of phenolic compounds and other chemical defenses. By contrast, well-drained land, such as Juata Laut 2, is a perfect thriving environment for optimal plant growth. Notwithstanding, it is important to ponder that overly fertile land can adversely nurture ideal conditions for pest development. Thus, both nutrient deficiencies and excesses can increase the risk of pest attack, as documented by Sarma et al. (2024), who noted that plant nutrient balance is a key factor in the natural control of mealybugs on papaya.

The results generally demonstrate the complex association between cultivation techniques and mealybug infestation. Intensive fertilization strengthens plant attractiveness to pests. While chemical pesticides only suppress populations temporarily, they may even disrupt ecological balance. Moreover, humidity and drainage strongly influence pest spread and survival. The other driving factor is plant age, which is found to modulate tissue susceptibility. These factors, in harmony, determine the dynamics of infestation. By implication, the results highlight that mealybug pest control on papaya in Tarakan City should engage an IPM that encompasses environmental, biological, and cultural measures. Balanced organic fertilizers, improved drainage systems, increased air circulation between plants, and the preservation of natural enemies by reducing the use of chemical pesticides will reduce the percentage of infested trees. This approach not only suppresses pest populations but also sustains the longevity of the papaya ecosystem.

Finally, the results acknowledge that different levels of infested trees and mealybug populations per tree in Tarakan City are affected by the intersection of environmental factors and cultivation techniques. Cultivation sites with high fertilization intensity and direct sunlight exposure show higher infestation rates. This is in strong contrast to those managed with organic fertilizers and a small number of pesticides. Moving forward, the mealybug population per infested tree remains relatively constant across sites implies that reducing the number of infested trees should become a priority. Implementing IPM sensitive to local conditions can be an efficacious measure to suppress mealybug infestations on papaya, while stimulating higher papaya yields.

5. Conclusion

This research documented the population and extent of mealybug infestation on papaya at seven cultivation sites in Tarakan City. The results acknowledge the dynamics of pest infestation. The percentage of trees infested with mealybugs ranged from 25.07% to 38.89%, while the average mealybug population on infested trees ranged from 199.52 to 224.59. This variation confirms the notion that environmental factors, in concert with cultivation techniques, play a pivotal role in mealybug growth and populations. Sites with intensive use of chemical fertilizers and frequent pesticide applications can lead to increased plant nitrogen content and fewer natural enemies. Moreover, these measures are more likely to stimulate higher levels of infestation and mealybug populations. In comparison, cultivation sites rich with organic systems and botanical pesticides exhibit a lower rate of infestation because of a more balanced ecosystem and more sustained growth of natural predators. The research implications recommend that an environmentally friendly cultivation approach, with judicious fertilizer and pesticide management, can effectively suppress mealybug populations. However, this still calls for supportive land microclimate conditions. IPM principles are thereby strongly endorsed to maintain sustainable papaya production in tropical regions, such as Tarakan City.

Author Contributions: **Albert Fredrick:** Conceptualization, Methodology, Investigation, Data curation, Validation, Project administration. **Abdul Rahim:** Formal analysis, Data curation, Visualization. **Muh. Adiwena:** Writing – original draft; Writing – review & editing, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

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