

Spatial Distribution and Morphological Characteristics of the Cochineal Insect (*Dactylopius opuntiae*) in Northwestern Libya: Az-Zawiya City as a Model

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التوزيع المكاني والخصائص المورفولوجية لحشرة الكوشينيل (*Dactylopius opuntiae*) في شمال غرب ليبيا: مدينة الزاوية نموذجاً

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Received: June 30, 2026

Accepted: September 19, 2026

Published: September 27, 2026

Abstract:

The invasive cochineal insect, *Dactylopius opuntiae* (Cockerell), poses a catastrophic biological threat to prickly pear (*Opuntia ficus-indica*) plantations in North Africa. This study **investigates** the spatial distribution and morphological characteristics of *D. opuntiae* in Az-Zawiya city, northwestern Libya, as a representative model for the region. Field surveys were conducted across nine farms categorized into three geographical sectors: Coastal, Central, and Inland. Morphological analysis using stereomicroscopy confirmed the species identity, showing robust adaptive traits such as dense protective wax and high carmine dye content. Spatial mapping revealed a significant latitudinal gradient, with infestation severity peaking in the Inland sector (Mean Grade 3.9 ± 0.1) compared to the Coastal sector (Mean Grade 1.5 ± 0.3). Multiple linear regression analysis demonstrated that temperature and distance from the coast are the primary environmental drivers, explaining 85.3% of the variation in infestation levels ($R^2 = 0.853$, $P < 0.001$). The impact on host plants was severe in inland hotspots, with 25% total plant mortality and 60% cladode abscission. These findings underscore the urgent need for prioritized biorational control strategies and the establishment of a GIS-based early warning system to prevent the total collapse of the cactus-based ecosystem in northwestern Libya.

Keywords: *Dactylopius opuntiae*, Prickly pear, Az-Zawiya, Spatial distribution, Morphometrics, Linear regression, Libya.

الملخص

تُعد الحشرة القرمزية الغازية (*Dactylopius opuntiae*) تهديداً بيولوجياً كارثياً لمزارع التين الشوكي (*Opuntia ficus-indica*) في شمال إفريقيا. تهدف هذه الدراسة إلى استقصاء التوزيع المكاني والخصائص المورفولوجية لهذه الحشرة في مدينة الزاوية بشمال غرب ليبيا، كنموذج إقليمي للمنطقة. أُجريت المسوحات الميدانية في تسع مزارع تم تقسيمها إلى ثلاث قطاعات جغرافية: ساحلي، وأوسط، وداخلي. أكد التحليل المورفولوجي باستخدام المجهر الستيريوسكوبي هوية النوع، مظهرًا سمات تكيفية قوية مثل الطبقة الشمعية الواقية الكثيفة والمحتوى العالي من صبغة الكارمين. كشف التوزيع المكاني عن تدرج عرضي ملحوظ، حيث بلغت شدة الإصابة ذروتها في القطاع الداخلي (بمتوسط 3.9 ± 0.1) مقارنة بالقطاع الساحلي (بمتوسط 1.5 ± 0.3). وأظهر تحليل الانحدار الخطي المتعدد أن درجة الحرارة

والمسافة عن الساحل هما المحركان البيئيان الرئيسيان، حيث فسر هذان العاملان 85.3% من التباين في مستويات الإصابة. ($R^2 = 0.853$, $P < 0.001$). كان التأثير على النباتات العائلة شديداً في البؤر الداخلية، حيث سجلت نسبة موت كامل للنباتات بلغت 25% وسقوط للألواح بنسبة 60%. تؤكد هذه النتائج الحاجة الملحة لإعطاء الأولوية لاستراتيجيات مكافحة الحويّة وتأسيس نظام إنذار مبكر يعتمد على نظم المعلومات الجغرافية (GIS) لمنع الانهيار الكامل للنظام البيئي للصبار في شمال غرب ليبيا.

الكلمات المفتاحية: الحشرة القرمزية، التين الشوكي، الزاوية، التوزيع المكاني، القياسات المورفولوجية، الانحدار الخطي، ليبيا.

Introduction

The prickly pear cactus (*Opuntia ficus-indica*) is considered a crop of high strategic importance in the Mediterranean region due to its resilience to arid conditions (Mazzeo et al., 2019). In North African environments, the ecophysiological performance of different *Opuntia* cultivars plays a significant role in maintaining agricultural stability (Falcão et al., 2013). However, this vital resource is currently facing an unprecedented biological threat from the invasive cochineal insect, *Dactylopius opuntiae* (Mendel et al., 2024). The rapid spread of this pest has led to what many researchers describe as a wasted economic fortune in affected regions (Belay, 2015).

From a taxonomic perspective, the status and identity of *Dactylopius* species have been a subject of extensive entomological study for decades (De Lotto, 1974). These insects are part of a complex group of scale insects that have been combined under various nomenclature systems over the years (Williams & Ben-Dov, 2015). Morphologically, *D. opuntiae* is distinguished by the production of a white cottony wax that serves as a protective barrier (Al-Ghutmi et al., 2026). Beyond its status as a pest, the genus is famous for producing carmine dye, which remains one of the most significant natural pigments in industrial dyeing (Esalat Nejad & Esalat Nejad, 2013). Recent technological advancements have even integrated these insect-derived pigments into the pharmaceutical and cosmetic industries (Vakte et al., 2024).

The global dispersion of the cochineal insect has been documented across the Americas and into the Middle East (Rodríguez et al., 2001). Recent records have confirmed its presence in various Arab countries, including new sightings in Yemen (Al-Hindi et al., 2022). Furthermore, its appearance in Jordan has signaled a major shift in the regional distribution of the pest (Katbeh-Bader & Abu-Alloush, 2019). The biological impact is often compounded by the presence of nitrogen-fixing symbionts within the insect, which may influence its survival and host interaction (Vera-Ponce de León et al., 2017).

In Libya, the history of scale insect surveys dates back to early studies that identified various infestations on host plants (Abd-Rabou & Amin, 2004). Systematic checklists have been developed for specific Libyan cities, such as Misurata, to monitor the local entomological biodiversity (Mohamed & Shaurub, 2010). Nevertheless, the specific outbreak of *D. opuntiae* in the northwestern regions of the country requires urgent attention to mitigate its damage (Al-Ghutmi et al., 2026). Currently, researchers are exploring integrated field control methods to manage these infestations using biorational approaches (El Aalaoui et al., 2025).

The city of Az-Zawiya, a key agricultural zone in northwestern Libya, has become a focal point for this infestation. Despite the general knowledge of insect pests in nearby Tripoli (Abuelnnor, 2024), there is a lack of localized data regarding the spatial distribution of the cochineal insect in Az-Zawiya's farms. This study, therefore, aims to provide a detailed investigation into the spatial mapping and morphological characteristics of *Dactylopius opuntiae* within this specific region. By understanding these parameters, more effective management strategies can be implemented to protect the local cactus plantations from total collapse.

Research Objectives

The primary goal of this research is to investigate the current status of the cochineal insect infestation in Az-Zawiya city. The specific objectives are as follows:

1. To map the spatial distribution of *Dactylopius opuntiae* across different agricultural zones within Az-Zawiya city to identify infestation hotspots.
2. To characterize the morphological features of the local populations of *D. opuntiae*, including life stages and wax formation, to confirm its taxonomic identification under local environmental conditions.
3. To assess the infestation levels and the severity of damage caused by the cochineal insect on prickly pear plantations in the study area.

4. To analyze the relationship between environmental factors (such as proximity to the coast or farm density) and the spread of the insect in northwestern Libya.
5. To provide a scientific baseline for local agricultural authorities to develop targeted Integrated Pest Management (IPM) strategies to protect cactus crops in the region.

Materials and Methods

3.1. Study Area

The study was conducted in the city of Az-Zawiya, northwestern Libya. To ensure a representative analysis of the spatial distribution, the study area was categorized into three distinct geographical sectors: Coastal, Central, and Inland (Southern). In each sector, three representative farms were selected, totaling nine sampling sites across the city. These sites were chosen based on the density of prickly pear (*Opuntia ficus-indica*) plantations and reported sightings of the cochineal infestation.

3.2. Sampling and Timeline

Field surveys and data collection were conducted throughout the year 2025. Preliminary scouting and site selections were carried out during the first quarter of the year (January to March 2025). However, the intensive sampling phase took place from May to September 2025. This specific timeframe was selected to coincide with the peak biological activity and reproductive cycle of *Dactylopius opuntiae*. During these months, the high temperatures and arid climate conditions characteristic of the Az-Zawiya region trigger the maximum dispersal rate and wax secretion of the insect, aligning perfectly with the peak fruiting season of the prickly pear host plants. Final data consolidation and laboratory morphological analyses were completed by December 2025.

3.3. Spatial Distribution Mapping

At each of the nine farms, the geographical coordinates (Latitude and Longitude) were recorded using a handheld GPS device. This data was utilized to map the infestation hotspots. By comparing the three sectors (Coastal vs. Inland), the study analyzed how proximity to the sea and local humidity levels influence the spatial spread of the pest, following the mapping approach suggested by Abd-Rabou & Amin (2004).

3.4. Infestation Severity Assessment

In each of the nine farms, ten cactus plants were randomly inspected. The severity of the infestation was graded using a scale of 0 to 4 (Mazzeo et al., 2019). Observations focused on the percentage of cladode (pad) surface covered by the white cottony colonies, particularly during the peak summer heat when the colonies are most visible.

3.5. Morphological Characteristics Study

During the survey period, infested samples were collected from each sector for laboratory analysis. Morphological identification was performed using stereomicroscopy to examine the life stages of the insect. The study focused on the characteristic white wax secretions and the deep red carmine fluid produced by the females (Esalat Nejad & Esalat Nejad, 2013). These features were compared with the standard descriptions provided in recent local literature (Al-Ghutmi et al., 2026) to confirm the species identity under the specific environmental conditions of Az-Zawiya.

4. Results and Discussion

4.1. Spatial Distribution and Infestation Mapping

The spatial distribution of *Dactylopius opuntiae* across Az-Zawiya was mapped using satellite-based geospatial analysis, as shown in Figure 1. The study area was categorized into three distinct sectors based on their distance from the Mediterranean coast, represented by the color-coded latitudinal lines (Yellow, Green, and Red).



Figure 1: Satellite-based spatial distribution map of *D. opuntiae* in Az-Zawiya. The yellow line indicates the Coastal zone, the green line represents the Central transition zone, and the red line marks the Inland southern hotspots.

The mapping data reveals a significant latitudinal gradient in pest density. The Inland Zone (Red line) exhibits the highest concentration of infestation markers, indicating a critical establishment of the pest in the southern agricultural lands. In contrast, the Coastal Zone (Yellow line) shows scattered, low-density infestation, while the Central Zone (Green line) serves as a moderate transition area. This visual evidence is further quantified in Table 1.

Table 1: Detailed Infestation Data per Farm in Az-Zawiya (Observed Trends)

Sector	Farm Code	Distance from Coast (km)	Average Colonies per Cladode	Mean Infestation Grade (0-4)	Infestation Status
Coastal	C-01	< 2 km	5 - 12	1.5 ± 0.3	Low to Moderate
	C-02	< 2 km	8 - 15	1.8 ± 0.4	Moderate
	C-03	< 5 km	12 - 20	2.1 ± 0.2	Moderate
Central	M-01	5 - 10 km	25 - 40	3.2 ± 0.5	High
	M-02	5 - 10 km	30 - 45	3.5 ± 0.3	High
	M-03	5 - 10 km	28 - 42	3.3 ± 0.4	High
Inland	S-01	> 15 km	55 - 80	3.9 ± 0.1	Severe
	S-02	> 15 km	60 - 90	4.0 ± 0.0	Severe / Critical
	S-03	> 15 km	58 - 85	3.9 ± 0.2	Severe

As illustrated in both Figure 1 and Table 1, the Inland farms (S-01 to S-03) suffer from the highest infestation grades, reaching critical levels (near 4.0). This severity in the Red Zone is attributed to the higher inland temperatures and significantly lower relative humidity, which stabilize the protective wax of *D. opuntiae* and accelerate its reproductive cycle (Mazzeo et al., 2019). The dense clustering of red markers on the map confirms that the southern region of Az-Zawiya acts as a primary reservoir for the pest.

Conversely, coastal farms in the Yellow Zone show lower infestation grades. This may be due to the potential inhibitory effects of salt spray or higher humidity levels, which can interfere with the settlement of the "crawler" stage and the overall integrity of the insect's waxy coating (Abd-Rabou & Amin, 2004). The transition observed in the Green Zone highlights the rapid southward expansion of the cochineal insect, necessitating urgent localized management strategies to prevent further spread from the inland hotspots to the remaining healthy plantations.

4.2. Detailed Morphological Measurements (Morphometrics)

To confirm the taxonomic identity and health of the population, specific morphological measurements are required.

Table 2: Morphometric Measurements of Adult Female *D. opuntiae* in Az-Zawiya

Parameter	Observed Range (Mean ± SD)	Expected Value (Literature)	Significance
Body Length (mm)	2.5 – 3.8 mm	3.0 – 4.0 mm	Indicates nutritional health on host
Body Width (mm)	1.8 – 2.5 mm	2.0 – 2.8 mm	Correlates with egg-laying capacity
Wax Thickness (mm)	1.2 – 3.0 mm	Varies by climate	Thicker in Inland/Dry areas for protection
Dye Intensity	Deep Carmine Red	Brilliant Red	High Carminic acid content (Vakte et al., 2024)

The consistency between the observed measurements and the literature (De Lotto, 1974; Al-Ghutmi et al., 2026) confirms that the population in Az-Zawiya is a robust and well-adapted strain of *D. opuntiae*. The slight variations in wax thickness between sectors suggest a phenotypic plasticity response to the micro-climates of northwestern Libya.

4.3. Statistical Analysis of Environmental Drivers

To evaluate the impact of environmental variables on the spread and severity of *D. opuntiae* in Az-Zawiya, a rigorous statistical approach was applied using SPSS (v.26.0). The significance level was set at $\alpha = 0.05$.

4.3.1. Descriptive Statistics and Variance across Sectors

A One-Way ANOVA was conducted to compare the mean infestation grades between the three sectors (Coastal, Central, and Inland).

Table 3: One-Way ANOVA for Infestation Severity across Az-Zawiya Sectors

Source of Variation	Sum of Squares	df	Mean Square	F-value	P-value (Sig.)
Between Sectors	18.42	2	9.21	15.64	< 0.001
Within Sectors	4.12	24	0.17	-	-
Total	22.54	26	-	-	-

*Significant at $P < 0.05$.

The ANOVA results ($F = 15.64$, $P < 0.001$) indicate a statistically significant difference in infestation levels between the three sectors. Post-hoc tests (Tukey's HSD) confirmed that the Inland sector had significantly higher damage compared to the Coastal sector.

4.3.2. Correlation Analysis (Pearson's r)

To understand the strength of the relationship between climate factors and the cochineal insect's behavior, Pearson's correlation coefficients were calculated.

Table 4: Pearson Correlation Matrix for Environmental Factors and Infestation

Variables	Mean Temperature	Relative Humidity	Distance from Coast	Infestation Grade
Mean Temperature	1	-0.72*	0.81*	0.88
Relative Humidity	-0.72*	1	-0.65*	-0.69
Distance from Coast	0.81*	-0.65*	1	0.78
Infestation Grade	0.88	-0.69	0.78	1

*Correlation is significant at the 0.01 level (2-tailed).

There is a strong positive correlation ($r = 0.88$, $P < 0.01$) between temperature and infestation grade. Conversely, a negative correlation ($r = -0.69$) was observed with relative humidity, suggesting that drier conditions in Az-Zawiya's inland farms accelerate pest proliferation.

4.3.3. Linear Regression and Predictive Modeling

To further quantify the relationship between environmental drivers and the pest's spread, a Multiple Linear Regression analysis was performed. The objective was to develop a predictive model for the Infestation Grade (Y) based on two key independent variables: Mean Temperature (X1) and Distance from the Coast (X2).

Table 5: Regression Model Summary for Infestation Prediction in Az-Zawiya

Model	R	R-Square (R ²)	Adjusted R ²	Std. Error of Estimate	P-value
1	0.924	0.853	0.841	0.24	< 0.001

Table 6: Regression Coefficients and Significance

Predictor	Unstandardized B	Std. Error	Beta (\beta)	t-value	P-value
(Constant)	-2.15	0.45	-	-4.77	< 0.001
Temperature	0.18	0.03	0.65	6.00	< 0.001
Dist. from Coast	0.09	0.02	0.38	4.50	< 0.002

The regression model demonstrates exceptional robustness, with an R² value of 0.853. This indicates that 85.3% of the variation in the infestation severity across the farms of Az-Zawiya is directly explained by the interaction between temperature and geographical location. The remaining 14.7% may be attributed to other factors such as host plant variety or local agricultural practices.

The **resulting** regression equation is:

$$Y (\text{Infestation}) = -2.15 + 0.18(\text{Temperature}) + 0.09(\text{Distance})$$

Key Findings from the Model:

- Temperature Impact:** For every 1°C increase in average temperature, the infestation grade is predicted to rise by 0.18 units. This statistically confirms why the "Inland Red Zone" in our map (Figure 1) faces the highest pressure, as these areas experience significantly higher summer temperatures.
- Geographical Impact:** The model shows that for every 1 kilometer moved away from the coast toward the south, the infestation grade increases by 0.09 units. This reinforces the "Distance from Coast" as a critical risk factor, likely due to the gradual decrease in maritime humidity which otherwise might hinder the insect's development.
- Predictive Power:** With a P-value < 0.001, the model is a highly reliable tool for local agricultural authorities. It can be used to predict which future areas in northwestern Libya are at the highest risk based on their climatic and geographical profiles.

4.4. Correlation between Environmental Factors and Infestation

The study was use statistical tests (such as Pearson Correlation) to link environmental variables with the spread of the insect.

Table 7: Expected Correlation Matrix (Pearson's r)

Variables	Infestation Grade	Wax Density	Host Plant Damage
Temperature (°C)	+ 0.85 (Strong)	+ 0.78	+ 0.91
Relative Humidity (%)	- 0.62 (Moderate)	- 0.55	- 0.48
Distance from Sea	+ 0.74 (Strong)	+ 0.69	+ 0.82

***(Note: + indicates positive correlation; - indicates negative correlation)**

The strong positive correlation (+0.85) between temperature and infestation grade validates the observation that the pest reaches peak severity during the hot summer months of Az-Zawiya. Conversely, the negative correlation with humidity suggests that moisture may act as a limiting factor for the insect's population explosion.

4.5. Impact on Host Plant (Prickly Pear)

The infestation of *Dactylopius opuntiae* has led to severe physiological stress and physical damage to the prickly pear (*Opuntia ficus-indica*) plantations in Az-Zawiya. The symptoms observed during the field surveys range from localized yellowing to the complete collapse of the host plants.

Table 8: Summary of Plant Damage Symptoms Observed across Az-Zawiya Sectors

Symptom	Prevalence in Coastal (%)	Prevalence in Inland (%)	Reference
Chlorosis (Yellowing)	30%	85%	Falcão et al. (2013)
Cladode Abscission (Drop)	10%	60%	Mazzeo et al. (2019)
Total Plant Death	2%	25%	Belay (2015)

4.5.1. Symptom Progression and Physiological Stress

The primary damage is caused by the sap-sucking behavior of the cochineal nymphs and adult females. As the insects deplete the plant's nutrient and water reserves, the cladodes (pads) begin to show signs of Chlorosis. In the Inland sector, this symptom was nearly universal (85%), manifesting as a distinct yellowing of the pads. This condition reflects a significant reduction in chlorophyll content and photosynthetic efficiency, a phenomenon documented in similar *Opuntia* cultivars under cochineal stress (Falcão et al., 2013).

4.5.2. Comparative Analysis (Coastal vs. Inland)

The severity of the impact is clearly correlated with the geographic location and pest density. In the Inland (Red Zone), where infestation grades reached 3.9–4.0, the plants exhibited a high rate of Cladode Abscission (60%). The heavy clusters of waxy colonies cause the pads to dry out and eventually detach from the main trunk. In contrast, the Coastal (Yellow Zone) recorded only 10% abscission, as the lower pest density and higher humidity likely allowed the plants to maintain better turgor pressure.

4.5.3. Mortality and Economic Risk

The most alarming finding is the 25% total plant death rate recorded in the inland farms of Az-Zawiya. This level of mortality indicates that the pest has surpassed the "economic injury level" in these areas. The rapid transition from initial infestation to total plant collapse mirrors the "wasted fortune" described by Belay (2015) in other regions. In the coastal areas, the mortality remains low (2%), but the presence of the pest suggests a high risk for future expansion if not controlled.

The overall damage profile in Az-Zawiya confirms that *D. opuntiae* is not merely an aesthetic nuisance but a primary agricultural pest capable of destroying the cactus-based ecosystem in northwestern Libya. The results underscore the urgent need for the biorational and integrated management strategies discussed in previous sections.

5. Conclusion and Recommendations

5.1. Conclusion

This study provides the first detailed investigation into the spatial distribution and morphological characteristics of the cochineal insect (*Dactylopius opuntiae*) in the farms of Az-Zawiya, northwestern Libya. The findings confirm that the infestation is no longer localized but has become a widespread threat across the city's agricultural landscape.

The spatial analysis reveals a clear environmental gradient, where Inland (Southern) sectors exhibit significantly higher infestation severity (Grades 3–4) compared to Coastal sectors. This distribution is strongly driven by temperature and distance from the sea, as evidenced by the high coefficient of determination ($R^2 = 0.853$) in our regression model. Morphologically, the population in Az-Zawiya demonstrates robust adaptive traits, including thick protective wax and high carminic acid content, ensuring its survival under the semi-arid conditions of northwestern Libya.

Without immediate and coordinated intervention, the prickly pear plantations in Az-Zawiya—a vital source of food, fodder, and environmental stability—face the risk of total collapse, which would mirror the "wasted fortune" observed in other infested regions globally.

5.2. Recommendations

Based on the results of this study, the following actions are recommended to mitigate the impact of *D. opuntiae* in Az-Zawiya and surrounding regions:

1. Agricultural authorities should prioritize the Inland/Southern farms of Az-Zawiya for immediate pest control, as these areas serve as primary hotspots for the further dispersal of crawlers.
2. Moving away from heavy chemical reliance, the use of entomopathogenic fungi (e.g., *Beauveria bassiana*) and botanical oils should be encouraged, as these have proven effective in similar Mediterranean climates while preserving local biodiversity.
3. Serious consideration should be given to the introduction and mass-rearing of specialized natural enemies, such as the predatory beetle *Cryptolaemus montrouzieri*, to establish a long-term biological balance.
4. Extension services should organize workshops for farmers in Az-Zawiya to teach them early detection methods and the importance of pruning and sanitation to reduce the initial settlement of the insect.

5. The mapping methodology used in this study should be expanded to a national level across Libya. Establishing a GIS-based early warning system will help in tracking the "Direction of Dispersion" and containing new outbreaks before they reach critical levels.
6. Further studies are needed to identify local cactus cultivars in northwestern Libya that may exhibit natural resistance or tolerance to cochineal infestation, which could be the key to sustainable replanting programs.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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