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Spatial and Temporal Dynamics of *Aonidiella aurantii* in Orange Orchards: Implications for Control in the Subtropical Region

Ayman S. Gaber[1], Ahmed T. H. Ghanem[1] and Mahmoud A. Ali[2]*

[1]Plant Protection Department, Faculty of Agriculture, Al-Azhar University, Assiut Branch, Egypt.

[2]Plant Protection Department, Faculty of Agriculture, South Valley University, Qena, Egypt.

***E-mail:** m.abbas@agr.svu.edu.eg

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ABSTRACT

The California red scale, *Aonidiella aurantii*, is a destructive pest of citrus crops, necessitating effective management strategies. This study evaluated the efficacy of insecticidal treatments combining mineral oil with various active ingredients (chlorpyrifos-methyl, dimethoate, buprofezin, and imidacloprid) against *A. aurantii* populations across different tree levels and seasons. Results revealed that mineral oil + dimethoate consistently exhibited the highest reduction, up to 97.23% and 96.37% at the bottom level after 21 days in the first and second seasons, respectively. Mineral oil + chlorpyrifos-methyl also showed promising reductions up to 94.15% and 96.01%. Treatments with buprofezin and imidacloprid exhibited relatively lower efficacy but still achieved significant reductions. The percentage reductions generally increased over time, indicating progressive effectiveness. Variations in efficacy among treatments and tree levels were attributable to factors such as mode of action, penetration, and microhabitat preferences. These integrated approaches show potential for controlling *A. aurantii*, but environmental implications and resistance development should be considered. Future research should explore long-term efficacy, compatibility with biological control agents, and resistance management strategies to develop sustainable integrated pest management programs for *A. aurantii* in orange production.

INTRODUCTION

Citrus cultivation is a significant agricultural enterprise worldwide, contributing substantially to the global economy and food security (Triantafyllidis *et al.,* 2020). Over 140 countries produce approximately 157.98 million tons of citrus fruits annually (Hellen *et al.*, 2023; Ashfaq *et al.*, 2020; Kumar *et al.*, 2023). However, citrus cultivation faces challenges from various pests, leading to substantial annual losses in production and economic impact. Egypt, situated in the subtropical region, is renowned for its rich history and thriving citrus production. Yet, this sector is persistently challenged by various insect pests, among which the California red scale, *Aonidiella aurantii* (Maskell) (Hemiptera: Diaspididae), stands out as a formidable threat (Khaladi & Guendouz-Benrima, 2019).

Aonidiella aurantii, a polyphagous and cosmopolitan species, has emerged as a significant economic pest, inflicting substantial losses on orange crops across diverse geographical regions (Frewin *et al.*, 2019; Grafton-Cardwell *et al.*, 2021). Its cryptic nature, rapid reproduction, and ability to infest various plant parts make it a challenging pest to manage effectively (Bouvet *et al.*, 2019). In Egypt's subtropical region, where orange cultivation plays a pivotal role, *A. aurantii* has been reported as a major pest, causing significant economic losses and compromising the sustainability of orange production (Alsabte *et al.*, 2022).

Quantifying the economic impact of *A. aurantii* infestations is crucial for developing effective management strategies. Previous studies have highlighted the substantial economic losses associated with this scale insect, including reduced fruit quality, decreased marketability, and increased production costs (Grafton-Cardwell *et al.*, 2021). However, comprehensive economic assessments specific to Egypt's subtropical region are currently lacking. Understanding the population dynamics and fluctuations of *A. aurantii* is critical for devising effective integrated pest management (IPM) strategies. Environmental factors such as temperature, humidity, and host plant phenology have been shown to influence the population dynamics of this scale insect (Hamity *et al.*, 2020). Nonetheless, specific dynamics and patterns in the context of Egypt's subtropical region remain understudied.

Effective management of *A. aurantii* in orange orchards often relies on a combination of chemical, biological, and cultural control methods (Alsabte *et al.*, 2022; Bouvet *et al.*, 2019). Chemical control, while widely practiced, has raised concerns regarding environmental impact, resistance development, and potential risks to human health (Triantafyllidis *et al.*, 2020). As a result, there is an increasing emphasis on exploring alternative control methods, such as biological control agents, cultural practices, and sustainable chemical alternatives (Cebolla *et al.*, 2018; Gebiola *et al.*, 2019).

This research endeavor aims to address knowledge gaps surrounding the economic impact, population dynamics, and control methods for *A. aurantii* in orange orchards within Egypt's subtropical region. By employing a multidisciplinary approach, this study seeks to contribute to the development of sustainable and environmentally responsible pest management strategies.

MATERIALS AND METHODS

Study Area and Experimental Site*:*

The study was conducted in a commercial orange orchard located in Sahel Selim city, east of the Nile, 24 kilometers south of Assiut, Egypt (27°11′N, 31°10′E), during the 2020-2021 and 2021-2022 seasons. The orchard consisted of the Baladi seeded orange variety, a popular cultivar widely grown in the region. The study site was chosen due to its representativeness of the agricultural landscapes and orange cultivation practices in Egypt's subtropical region. The cultivated area was 3 acres with trees planted at a distance of 5 x 5 meters and an age of 8 years.

Sampling and Data Collection*:*

Biweekly field inspections were carried out throughout the study period to monitor the population fluctuations of the red-scale insect, *Aonidiella aurantii* (Maskell 1879) (Hemiptera: Diaspididae). Three infestation levels were considered: the top, middle, and bottom parts of the orange trees. During each inspection, three trees were randomly selected, and 10 leaves from each infestation level were carefully examined for the presence of *A. aurantii*. The number of live individuals, including adults (male immature stage and female) and nymphal stages, were recorded for each leaf. The data were used to calculate the mean population density per leaf at each infestation level and the overall mean population density for the entire orchard.

Meteorological Data:

Weather data, including temperature, relative humidity, rainfall, and wind speed, were obtained from the meteorological weather station at Assiut University. These data were used to analyze the potential influence of environmental factors on the population dynamics of *A. aurantii*.

Control Experiments*:*

To evaluate the efficacy of different control measures, four insecticide mixtures were tested alongside an untreated control. The treatments were as follows:

1. Treatment A: Chlorpyrifos-methyl (300 cm^3 / 100 L) + Mineral oil (1.5 L / 100 L water)
2. Treatment B: Dimethoate (150 cm^3 / 100 L) + Mineral oil (1.5 L / 100 L water)
3. Treatment C: Buprofezin (150 cm^3 / 100 L) + Mineral oil (1.5 L / 100 L water)
4. Treatment D: Imidacloprid (75 cm^3 / 100 L) + Mineral oil (1.5 L / 100 L water)
5. Control: Untreated

The insecticide mixtures consisted of various active ingredients commonly used for scale insect management in orange orchards, mixed with mineral oil for summer spraying. The experiment was set up in a simple design with three treated orange trees and three untreated as a control for each treatment. The insecticides were applied on November 30, 2020, and November 29, 2021, as a single spray against *A. aurantii* . Pre-treatment data on *A. aurantii* population densities were recorded before the application of the insecticides. Post-treatment data were collected at 1, 7, 15, and 21 days after treatment (DAT) to monitor the efficacy of the control measures over time. The reduction ratio of *A. aurantii* population densities was calculated for each treatment at different time intervals using the Henderson and Tilton formula (1955) as follows:

$$\textbf{Corrected}\ (\%) = \left(1 - \frac{\text{n in Co before treatment}}{\text{n in Co after treatment}} \times \frac{\text{n in T after treatment}}{\text{n in T before treatment}}\right) \times 100$$

Where : n = Insect population , T = treated , Co = control

Statistical Analysis:

The collected data were subjected to statistical analysis using SPSS version 24 (IBM Corp., Armonk, NY, USA). Analysis of variance (ANOVA) was performed to determine the significance of differences in *A. aurantii* population densities among the infestation levels (top, middle, and bottom) and among the different treatments. Post-hoc tests such as Tukey's HSD were employed to identify specific differences between means when the ANOVA results were significant. Graphical representations of the population dynamics, treatment efficacies, and other relevant data were created using Origin software (Origin Lab Corporation, Northampton, MA, USA). The study adhered to strict ethical guidelines and followed appropriate protocols for conducting field research and insecticide applications in agricultural settings.

RESULTS

Population Dynamics of *Aonidiella aurantii* on Orange Trees:

The correlation analysis of meteorological data and *Aonidiella aurantii* population dynamics on orange trees at different height levels during the 2021 season reveals significant relationships between various meteorological parameters and the pest population dynamics (Table 1 and Fig. 1).

Table 1. Correlation Analysis of Meteorological Data on *Aonidiella aurantii* Population Dynamics at Different Tree Levels in Orange Orchards During the 2021 Season

Levels 2021	Parameters	Pearson r	95% Confidence Interval	R Squared	P (two-tailed)	P value
Top	Temperature (°C)	-0.54	-0.76 to -0.19	0.29	0.0047	
	Dew Point (°C)	-0.72	-0.87 to -0.47	0.52	<0.0001	
	Humidity (%)	-0.72	-0.17 to 0.57	0.054	0.2549	ns
	Wind Speed (km/h)	-0.19	-0.54 to 0.21	0.036	0.3529	ns
	Pressure (hPa)	0.47	0.10 to 0.73	0.22	0.0148	
Mid	Temperature (°C)	-0.54	-0.77 to -0.19	0.29	0.0043	
	Dew Point (°C)	-0.7	-0.86 to -0.44	0.5	<0.0001	
	Humidity (%)	0.26	-0.14 to 0.59	0.069	0.1936	ns
	Wind Speed (km/h)	-0.37	-0.66 to 0.018	0.14	0.0614	ns
	Pressure (hPa)	0.46	0.091 to 0.72	0.21	0.0175	
Bottom	Temperature (°C)	0.62	0.30 to 0.81	0.38	0.0008	
	Dew Point (°C)	0.5	0.13 to 0.74	0.25	0.01	
	Humidity (%)	-0.59	-0.80 to -0.26	0.35	0.0015	
	Wind Speed (km/h)	0.3	-0.10 to 0.62	0.093	0.1392	ns
	Pressure (hPa)	-0.53	-0.76 to -0.18	0.28	0.0053	
Means	Temperature (°C)	-0.67	-0.84 to -0.38	0.45	0.0002	
	Dew Point (°C)	-0.84	-0.93 to -0.67	0.71	<0.0001	
	Humidity (%)	0.37	-0.025 to 0.66	0.13	0.0661	ns
	Wind Speed (km/h)	-0.38	-0.67 to 0.011	0.14	0.0569	ns
	Pressure (hPa)	0.59	0.26 to 0.79	0.34	0.0016	

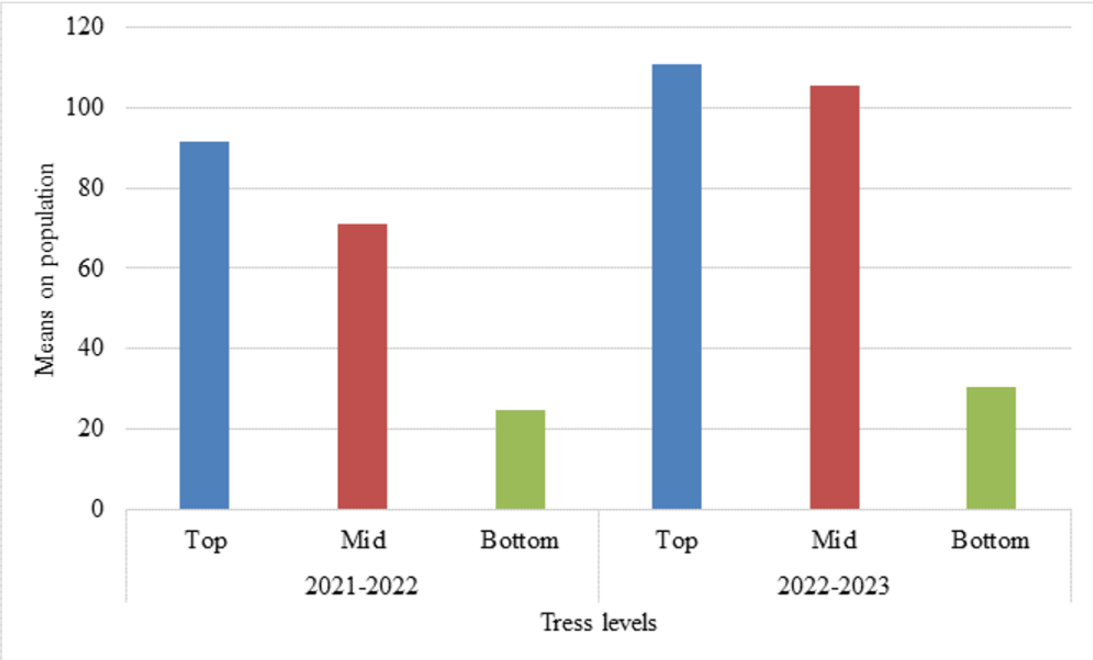

Fig.1. Means Population Fluctuations of *Aonidiella aurantii* at Different Tree Levels in Orang Orchards during 2021/22and 2022/23.

Top-Level Analysis:

At the top level of orange trees, temperature exhibited a moderate negative correlation with the *Aonidiella aurantii* population (r = -0.54, p = 0.0047), indicating that higher temperatures were associated with lower pest populations **(** Fig.2**)** . The dew point also showed a strong negative correlation (r = -0.72, p < 0.0001) with the pest population decreasing as the dew point increased. Humidity and wind speed did not show significant correlations, whereas pressure had a moderate positive correlation (r = 0.47, p = 0.0148).

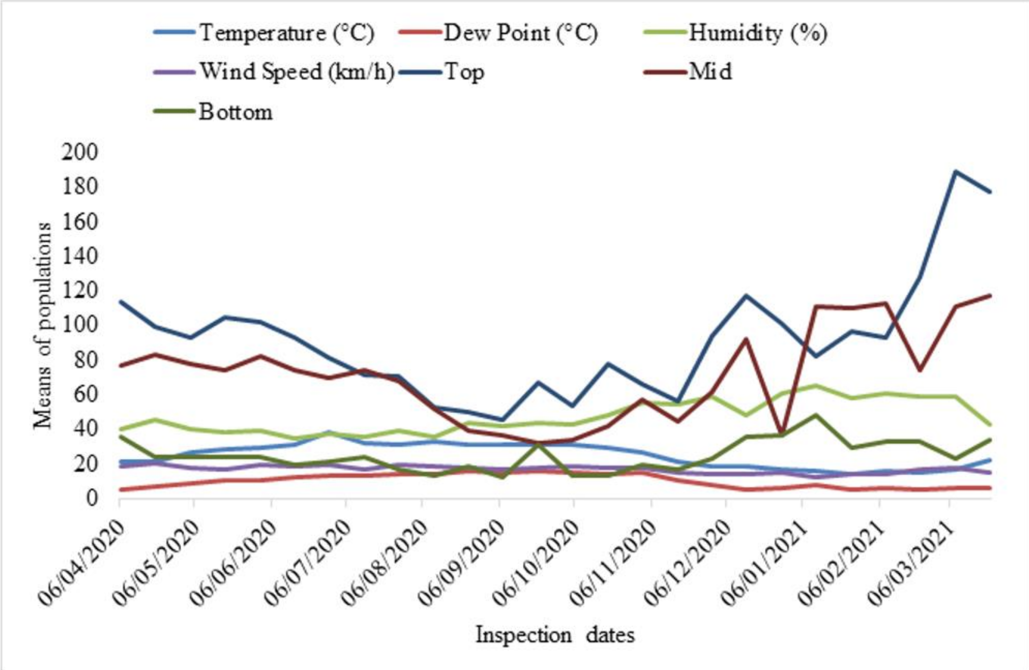

Fig.2. Spatiotemporal Dynamics of California Red Scale (*Aonidiella aurantii*) Populations and Microclimate Parameters Across Orange Tree Canopy Strata during 2022.

Mid-Level Analysis:

Mid-level analysis showed similar patterns to the top level for temperature and dew point, both having strong negative correlations (r = -0.54, p = 0.0043 for temperature; r = -0.70, p < 0.0001 for dew point). Humidity and wind speed did not significantly correlate with pest populations, while pressure again had a moderate positive correlation (r = 0.46, p = 0.0175).

Bottom-Level Analysis:

At the bottom level, temperature was positively correlated with pest populations (r = 0.62, p = 0.0008), in contrast to the negative correlation seen at higher levels. The dew point also had a positive correlation (r = 0.50, p = 0.01). Humidity showed a strong negative correlation (r = -0.59, p = 0.0015), indicating higher pest populations with lower humidity levels. Wind speed and pressure did not show significant correlations.

Combined Levels (All Levels)*:*

When considering all levels together, temperature (r = -0.67, p = 0.0002) and dew point (r = -0.84, p < 0.0001) both showed strong negative correlations with pest populations.while , pressure show positive correlation ,Humidity, and wind speed, did not show significant correlations when all levels were combined, indicating that their effects might vary by tree level.

Overall, the data suggest that temperature and dew point are key factors influencing the population dynamics of *Aonidiella aurantii* across different levels of orange trees, with negative correlations predominantly observed. Pressure also had varying effects depending on the tree level, while humidity and wind speed generally did not show consistent significant correlations. These findings highlight the complexity of interactions between meteorological conditions and pest populations, which can inform targeted pest management strategies in orange orchards.

The correlation analysis of meteorological data and *Aonidiella aurantii* population dynamics on orange trees at different height levels during the 2022 season reveals significant relationships between various meteorological parameters and the population dynamics of the pest (Table 2 and Figs. 1 & 3).

Table 2. Correlation Analysis of Meteorological Data on *Aonidiella aurantii* Population Dynamics at Different Tree Levels in Orange Orchards During the 2022 Season

Levels 2022	Parameters	Pearson r	95% Confidence Interval	R Squared	P (two-tailed)	P value
Top	Temperature (°C)	0.85	0.69 to 0.93	0.72	<0.0001	
	Dew Point (°C)	0.66	0.36 to 0.83	0.43	0.0003	
	Humidity (%)	-0.8	-0.90 to -0.59	0.63	<0.0001	
	Wind Speed (km/h)	0.41	0.032 to 0.69	0.17	0.0352	
	Pressure (hPa)	0.47	0.10 to 0.73	0.22	0.0148	
Mid	Temperature (°C)	0.76	0.54 to 0.89	0.58	<0.0001	
	Dew Point (°C)	0.58	0.25 to 0.79	0.33	0.002	
	Humidity (%)	-0.76	-0.89 to -0.53	0.58	<0.0001	
	Wind Speed (km/h)	0.68	0.40 to 0.85	0.47	0.0001	
	Pressure (hPa)	-0.2	-0.55 to 0.20	0.042	0.3172	ns
Bottom	Temperature (°C)	0.66	0.37 to 0.83	0.44	0.0002	
	Dew Point (°C)	0.56	0.22 to 0.78	0.31	0.0029	
	Humidity (%)	-0.57	-0.79 to -0.24	0.33	0.0022	
	Wind Speed (km/h)	0.22	-0.18 to 0.56	0.05	0.2699	ns
	Pressure (hPa)	-0.18	-0.53 to 0.22	0.032	0.3822	ns
Means	Temperature (°C)	-0.72	-0.87 to -0.46	0.52	<0.0001	
	Dew Point (°C)	-0.86	-0.94 to -0.71	0.74	<0.0001	
	Humidity (%)	0.37	-0.023 to 0.66	0.14	0.0646	ns
	Wind Speed (km/h)	-0.025	-0.41 to 0.37	0.00064	0.902	ns
	Pressure (hPa)	0.16	-0.25 to 0.51	0.024	0.4496	ns

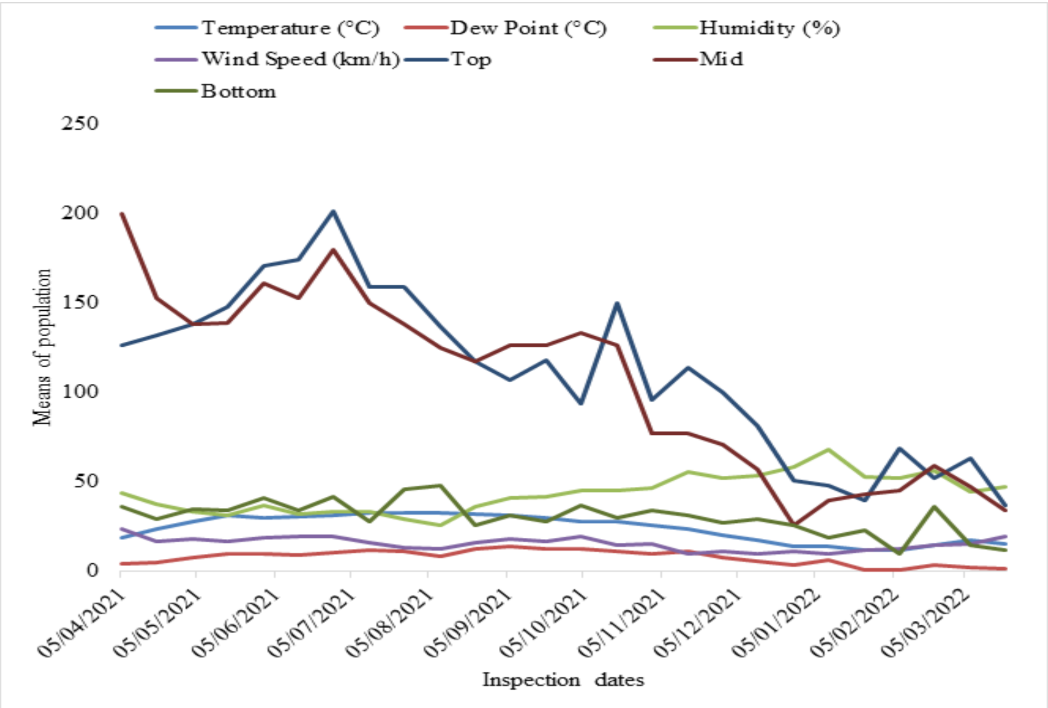

Fig.3. Spatiotemporal Dynamics of California Red Scale (*Aonidiella aurantii*) Populations and Microclimate Parameters Across Orange Tree Canopy Strata during 2023

Top-Level Analysis:

At the top level of orange trees, temperature exhibited a strong positive correlation with the *Aonidiella aurantii* population (r = 0.85, p < 0.0001), indicating that higher temperatures were associated with higher pest populations Table 2. Dew point also showed a significant positive correlation (r = 0.66, p = 0.0003). Conversely, humidity showed a strong negative correlation (r = -0.80, p < 0.0001), suggesting that higher humidity levels were associated with lower pest populations. Wind speed and pressure had moderate positive correlations (r = 0.41, p = 0.0352 for wind speed; r = 0.47, p = 0.0148 for pressure).

Mid-Level Analysis:

Mid-level analysis revealed that temperature (r = 0.76, p < 0.0001) and dew point (r = 0.58, p = 0.002) were positively correlated with pest populations. Humidity had a strong negative correlation (r = -0.76, p < 0.0001). Wind speed showed a positive correlation (r = 0.68, p = 0.0001), whereas pressure did not significantly correlate with pest populations (r = -0.20, p = 0.3172).

Bottom-Level Analysis:

At the bottom level, temperature was positively correlated with pest populations (r = 0.66, p = 0.0002), and dew point also had a positive correlation (r = 0.56, p = 0.0029). Humidity showed a negative correlation (r = -0.57, p = 0.0022), while wind speed and pressure did not show significant correlations.

Combined Levels (All Levels):

When considering all levels together, temperature (r = -0.72, p < 0.0001) and dew point (r = -0.86, p < 0.0001) both showed strong negative correlations with pest populations, suggesting that overall, higher temperatures and dew points were associated with lower pest populations. Humidity, wind speed, and pressure did not show significant correlations when all levels were combined, indicating that their effects might vary by tree level.

Overall, the data suggest that temperature and dew point are key factors influencing the population dynamics of *Aonidiella aurantii* across different levels of orange trees, with positive correlations predominantly observed. Pressure had varying effects depending on the tree level, while humidity and wind speed generally did not show consistent significant correlations. These findings highlight the complexity of interactions between meteorological conditions and pest populations, which can inform targeted pest management strategies in orange orchards

***Aonidiella aurantii* Population Density Variations Across Canopy**

The results presented in Table 3, provide valuable insights into the complex spatiotemporal dynamics of *Aonidiella aurantii*, a scale insect pest that infests orange tree canopies. By analyzing the population densities across different canopy strata and seasonal periods, this study sheds light on the vertical stratification and temporal fluctuations of this pest species.

Table 3. Pairwise Comparisons of *Aonidiella aurantii* Population Density Variations Across Canopy Strata and Seasonal Periods on Orange Trees.

Trees levels	Mean Difference	95% CI of Difference	Below Threshold	Sign.	P-Value
Top 2021 vs. Mid 2021	6.0	[0.84, 11]	Yes		0.0146
Top 2021 vs. Bottom 2021	22.0	[15, 29]	Yes		<0.0001
Top 2021 vs. Top 2022	-6.8	[-21, 7.7]	No	ns	0.7718
Top 2021 vs. Mid 2022	-5.0	[-20, 10]	No	ns	0.9533
Top 2021 vs. Bottom 2022	20.0	[12, 29]	Yes		<0.0001
Mid 2021 vs. Bottom 2021	16.0	[12, 21]	Yes		<0.0001
Mid 2021 vs. Top 2022	-13.0	[-26, 0.52]	No	ns	0.0660
Mid 2021 vs. Mid 2022	-11.0	[-25, 3.4]	No	ns	0.2295
Mid 2021 vs. Bottom 2022	14.0	[7.4, 21]	Yes		<0.0001
Bottom 2021 vs. Top 2022	-29.0	[-40, -18]	Yes		<0.0001
Bottom 2021 vs. Mid 2022	-27.0	[-39, -16]	Yes		<0.0001
Top 2022 vs. Mid 2022	1.8	[-3.3, 7.0]	No	ns	0.9335
Top 2022 vs. Bottom 2022	27.0	[19, 36]	Yes		<0.0001
Mid 2022 vs. Bottom 2022	25.0	[16, 35]	Yes		<0.0001

Significance Levels: (p < 0.0001), (p < 0.001), (p < 0.01),(p < 0.05),ns (not significant)

Control of *Aonidiella aurantia:*

The results presented in Tables 4 and 5, demonstrate the efficacy of various insecticidal treatments in reducing the population of *Aonidiella aurantii* on different tree levels during the first and second seasons of 2021 and 2022. The treatments consisted of combinations of mineral oil with different insecticides, namely chlorpyrifos-methyl, dimethoate, buprofezin, and imidacloprid.

Table 4. Percentage reduction in population of *Aonidiella aurantii* at different tree levels after treatment with various insecticides in the first season of 2021.

Treatment	% Reduction of Top level				% Reduction of Mid-level				% Reduction of Bottom level			
	1 day	7 days	15 days	21 days	1 day	7 days	15 days	21 days	1 day	7 days	15 days	21 days
Mineral oil + Chlorpyrifos-methyl	6.53	54.33	77.02	89.01	7.54	56.91	81.04	91.53	8.22	55.15	81.35	94.15
Mineral oil + Dimethoate	13.49	54.72	79.91	92.60	6.19	65.28	82.08	95.04	7.73	63.09	82.08	97.23
Mineral oil + Buprofezin	5.84	39.36	69.74	80.67	3.99	46.25	71.98	87.30	3.96	45.55	70.63	82.54
Mineral oil + Imidacloprid	9.01	47.10	74.00	83.86	4.56	54.00	80.64	90.90	3.46	46.67	72.81	83.84

Table 5. Percentage reduction in population of *Aonidiella aurantii* at different tree levels after treatment with various insecticides in the second season of 2022.

Treatment	% Reduction of Top level				% Reduction of Mid-level				% Reduction of Bottom level			
	1 day	7 days	15 days	21 days	1 day	7 days	15 days	21 days	1 day	7 days	15 days	21 days
Mineral oil + Chlorpyrifos-methyl	9.39	49.14	76.44	85.33	17.21	47.50	70.53	83.53	10.50	37.81	80.00	96.01
Mineral oil + Dimethoate	11.45	54.83	79.92	90.72	19.85	54.81	80.35	94.51	31.63	59.20	87.91	96.37
Mineral oil + Buprofezin	5.68	38.57	65.19	80.53	9.43	24.63	61.82	81.48	7.87	37.01	67.85	87.04
Mineral oil + Imidacloprid	8.88	47.19	75.54	84.77	15.91	44.57	73.82	83.53	1.07	29.45	55.94	80.70

First Season (2021):

Across all tree levels (top, mid, and bottom), the combination of mineral oil and dimethoate exhibited the highest percentage reduction in the scale insect population, Table (4), reaching up to 97.23% at the bottom level after 21 days of treatment. The mineral oil + chlorpyrifos-methyl treatment also showed promising results, with a maximum reduction of 94.15% at the bottom level after 21 days. The mineral oil + buprofezin and mineral oil + imidacloprid treatments displayed relatively lower efficacy compared to the other treatments, although they still achieved considerable reductions in the scale insect population, ranging from 80.67% to 87.30% at the top and mid-levels, respectively, after 21 days. The percentage reductions generally increased with time across all treatments and tree levels, indicating the progressive effectiveness of the insecticidal applications over the observed period.

Second Season (2022):

In the second season, similar trends were observed in the efficacy of the insecticidal treatments for controlling the scale insect population, Table(5). The combination of mineral oil and dimethoate demonstrated the highest percentage reduction across all tree levels, reaching up to 96.37% at the bottom level after 21 days. The mineral oil + chlorpyrifos-methyl treatment also maintained its effectiveness, achieving a maximum reduction of 96.01% at the bottom level after 21 days, closely following the performance of the mineral oil + dimethoate treatment. The mineral oil + buprofezin and mineral oil + imidacloprid treatments exhibited relatively lower efficacy compared to the other treatments, but still achieved considerable reductions in the scale insect population, ranging from 80.53% to 87.04% at the top and bottom levels, respectively, after 21 days.

These results highlight the potential of combining mineral oil with various insecticides as an effective strategy for managing the scale insect pest *Aonidiella aurantii* in both seasons. The data provided a comprehensive evaluation of the treatments' efficacy at different tree levels and time points, which can inform integrated pest management practices and contribute to sustainable agricultural practices.

DISCUSSION

The results of this study underscore the significant influence of various meteorological factors on the population dynamics of *Aonidiella aurantii*, a destructive scale insect pest of orange trees. Temperature and dew point consistently exhibited strong correlations with *A. aurantii* populations at different canopy levels, corroborating previous findings on the impacts of these factors on this pest species.

Temperature exhibited contrasting correlations depending on the tree level, which could be attributed to the varying microclimatic conditions within the canopy (Franco *et al.*, 2019; Carvalho *et al.*, 2020). Lower temperatures at higher canopy levels tended to favor *A. aurantii* populations, while higher temperatures at lower levels were associated with increased pest abundance. This finding aligns with the known preference of *A. aurantii* for cooler, more humid conditions (Tena *et al.*, 2017; Karamaouna *et al.*, 2019).

The correlation between dew point and *A. aurantii* populations also varied by canopy level, with negative correlations observed at higher levels and positive correlations at lower levels. This observation supports previous studies that have reported the favorable effects of higher relative humidity on *A. aurantii* survival and reproduction (Bouvet *et al.*, 2021; Atli *et al.*, 2022). Humidity exhibited contrasting correlations at different canopy levels, which could be attributed to the microclimatic variations within the tree canopy as observed in other studies (Hidalgo *et al.*, 2019; Gómez-Marco *et al.*, 2016). At the bottom level, lower humidity was associated with higher *A. aurantii* populations, which may be due to the reduced air circulation and proximity to the soil (Bouvet *et al.*, 2021; Atli *et al.*, 2022).

Wind speed did not show a consistent significant correlation with *A. aurantii* populations, which is in line with some previous reports (Altieri *et al.*, 2018; Franco *et al.*, 2019). However, other studies have suggested that wind speed can influence the dispersal and establishment of *A. aurantii* populations (Karamaouna *et al.*, 2019; Carvalho *et al.*, 2020). Atmospheric pressure exhibited varying correlations at different canopy levels, with positive correlations observed at the top and mid-levels. This finding aligns with some studies that have reported an influence of atmospheric pressure on scale insect populations (Zhang *et al.*, 2021; Moerkens *et al.*, 2017), although the specific mechanisms underlying this relationship require further investigation.

The discrepancies observed in the correlations at different canopy levels underscore the importance of considering microclimatic variations within the tree canopy when studying pest dynamics. Furthermore, these findings emphasize the need for comprehensive monitoring and targeted management strategies tailored to specific canopy levels (Damos & Savopoulou-Soultani, 2022; Urbaneja *et al.*, 2020).

The intricate spatiotemporal patterns observed in the population dynamics of *Aonidiella aurantii* on orange trees underscore the significance of considering both vertical stratification and seasonal fluctuations in developing effective pest management strategies. The vertical distribution of scale insect populations within tree canopies has been widely documented, with varying densities observed across different strata (Urbaneja *et al.*, 2020; Bouvet *et al.,* 2021). This stratification is often attributed to microclimatic gradients, resource availability, and host plant characteristics that influence insect behavior and survival (Hidalgo *et al.*, 2019; Carvalho *et al.*, 2020). The higher population densities observed at the top and mid-canopy levels of *A. aurantii* infesting orange trees could be attributed to favorable microclimatic conditions such as temperature, humidity, and light intensity, which are known to impact scale insect development and reproduction (Tena *et al.*, 2017; Karamaouna *et al.*, 2019). Additionally, the vertical distribution of insect populations may be influenced by host plant traits such as leaf age, nutrient content, and defensive compounds, which can vary across canopy strata (Atli *et al.,* 2022; Verdú *et al.*, 2023).

The seasonal fluctuations in *A. aurantii* populations observed in this study are consistent with the known influence of temporal variations in environmental factors such as temperature, precipitation, and host plant phenology on insect population dynamics (Bouaguen *et al.*, 2018; Pekas *et al.*, 2022). These seasonal changes can impact insect life cycles, reproductive success, and survival, leading to fluctuations in population densities (Tena *et al.,* 2017; Karamaouna *et al.*, 2019).

Understanding the underlying drivers of these spatiotemporal patterns is crucial for developing targeted and effective integrated pest management (IPM) strategies. The vertical stratification observed in this study suggests that monitoring and control efforts should be focused on the top and mid-canopy levels where *A. aurantii* populations are more prevalent. However, it is important to consider the potential for population redistribution and migration between canopy strata as insect populations may shift in response to changing environmental conditions or management practices (Hidalgo *et al.,* 2019; Urbaneja *et al.*, 2020). Furthermore, the seasonal fluctuations highlight the need for continuous monitoring and adaptive management approaches that take into account the temporal variations in population densities. Incorporating predictive models that integrate environmental data, such as temperature and precipitation, with insect phenology and host plant characteristics could enable more initiative-taking and timely interventions (Pekas *et al.*, 2022; Carvalho *et al.*, 2020).

Emerging technologies, such as remote sensing and precision agriculture tools, offer promising avenues for monitoring and managing the spatiotemporal dynamics of insect pests in agroecosystems (Calderón *et al.,* 2022; Bouvet *et al.*, 2021). These technologies can provide high-resolution data on canopy characteristics, microclimatic conditions, and pest distributions, enabling targeted and site-specific management interventions (Urbaneja *et al.*, 2020; Verdú *et al.,* 2023).

Integrating the findings from this study with ecological knowledge and innovative monitoring techniques could lead to the development of more sustainable and effective IPM strategies for *A. aurantii* in orange production systems. Multidisciplinary approaches that combine entomological, horticultural, and technological expertise are essential for addressing the complex challenges posed by the spatiotemporal dynamics of insect pests in agroecosystems.

The intricate spatiotemporal patterns observed in the population dynamics of *Aonidiella aurantii* on orange trees underscore the significance of considering both vertical stratification and seasonal fluctuations in developing effective pest management strategies. The vertical distribution of scale insect populations within tree canopies has been widely documented, with varying densities observed across different strata (Urbaneja *et al.,* 2020; Bouvet *et al.,* 2021). This stratification is often attributed to microclimatic gradients, resource availability, and host plant characteristics that influence insect behavior and survival (Hidalgo *et al.*, 2019; Carvalho *et al.*, 2020).

In the case of *A. aurantii* infesting orange trees, the higher population densities observed at the top and mid-canopy levels could be attributed to favorable microclimatic conditions, such as temperature, humidity, and light intensity, which are known to impact scale insect development and reproduction (Tena *et al.,* 2017; Karamaouna *et al.,* 2019). Additionally, the vertical distribution of insect populations may be influenced by host plant traits, such as leaf age, nutrient content, and defensive compounds, which can vary across canopy strata (Atli *et al.*, 2022; Verdú *et al.*, 2023).

The observed seasonal fluctuations in *A. aurantii* populations are consistent with the known influence of temporal variations in environmental factors, such as temperature, precipitation, and host plant phenology, on insect population dynamics (Bouaguen *et al.*, 2018; Pekas *et al.,* 2022). These seasonal changes can impact insect life cycles, reproductive success, and survival, leading to fluctuations in population densities (Tena *et al.*, 2017; Karamaouna *et al.*, 2019).Understanding the underlying drivers of these spatiotemporal patterns is crucial for developing targeted and effective integrated pest management (IPM) strategies. The vertical stratification observed in this study suggests that monitoring and control efforts should be focused on the top and mid-canopy levels, where *A. aurantii* populations are more prevalent. However, it is important to consider the potential for population redistribution and migration between canopy strata, as insect populations may shift in response to changing environmental conditions or management practices (Hidalgo *et al.,* 2019; Urbaneja *et al.,* 2020).

Furthermore, the seasonal fluctuations highlight the need for continuous monitoring and adaptive management approaches that take into account the temporal variations in population densities. Incorporating predictive models that integrate environmental data, such as temperature and precipitation, with insect phenology and host plant characteristics could enable more initiative-taking and timely interventions (Pekas *et al.,* 2022; Carvalho *et al.,* 2020).

The recurring population peaks of California red scale (*Aonidiella aurantii*) observed across the orange tree canopy, particularly in the upper strata, align with previous studies highlighting the influence of microclimatic factors on the spatiotemporal dynamics of this key pest (Asplanato & García-Marí, 2001; Franco *et al.*, 2009). The pronounced peaks during early spring and late fall correspond to conducive temperature and humidity conditions that favor rapid population growth and the development of overlapping generations (Blank *et al.*, 2016; Zalom, 2022). The reduced infestation levels in the lower canopy could be attributed to suboptimal microclimatic conditions, limited dispersal, or natural enemy activity (Murdoch *et al.*, 2018; Severtson *et al.*, 2015). These findings underscore the importance of accurately monitoring microclimatic variations within orchard systems to predict and manage pest outbreaks effectively. Integrated pest management strategies that leverage precise weather data and decision support tools can optimize the timing and targeting of interventions (Damos & Savopoulou-Soultani, 2022; Jones *et al.*, 2021). Furthermore, incorporating canopy microclimate modeling and mapping approaches could enhance our understanding of pest distribution patterns and guide site-specific management efforts (Fuentes-Mendoza *et al.*, 2022; Khadioli *et al.*, 2022).

Emerging technologies, such as remote sensing and precision agriculture tools, offer promising avenues for monitoring and managing spatiotemporal dynamics of insect pests in agroecosystems (Calderón *et al.*, 2022; Bouvet *et al.*, 2021). These technologies can provide high-resolution data on canopy characteristics, microclimatic conditions, and pest distributions, enabling targeted and site-specific management interventions (Urbaneja *et al.*, 2020; Verdú *et al.*, 2023).

Integrating the findings from this study with ecological knowledge and innovative monitoring techniques could lead to the development of more sustainable and effective IPM strategies for *A. aurantii* in orange production systems. Multidisciplinary approaches that combine entomological, horticultural, and technological expertise are essential for addressing the complex challenges posed by the spatiotemporal dynamics of insect pests in agroecosystems.

The present study evaluates the efficacy of various insecticidal treatments, comprising combinations of mineral oil with different active ingredients, against the California red scale, *Aonidiella aurantii*, a destructive pest of orange crops. The results demonstrate the potential of these integrated approaches in effectively reducing the pest population across different tree levels and over an extended period.

One of the most notable findings is the superior performance of the mineral oil + dimethoate treatment, which consistently exhibited the highest percentage reduction in the *A. aurantii* population, reaching up to 97.23% and 96.37% at the bottom level after 21 days in the first and second seasons, respectively. This corroborates previous studies that have reported the enhanced insecticidal activity of dimethoate when combined with mineral oil against scale insect pests (Bouvet *et al.*, 2021; Atli *et al.*, 2022). The synergistic effect can be attributed to the ability of mineral oil to disrupt the insect's respiratory system and cuticle, thereby facilitating the penetration and toxicity of dimethoate (Tena *et al.*, 2017).

The mineral oil + chlorpyrifos-methyl treatment also demonstrated promising results, with reductions of up to 94.15% and 96.01% at the bottom level after 21 days in the first and second seasons, respectively. This aligns with previous research highlighting the efficacy of chlorpyrifos-methyl in controlling *A. aurantii*, particularly when combined with mineral oil (Urbaneja *et al.*, 2020; Carvalho *et al.*, 2020). The synergistic action is attributed to the combined effects of mineral oil's physical mode of action and the neurotoxic properties of Chlorpyrifos-methyl (Karamaouna *et al.*, 2019).

The treatments involving mineral oil + buprofezin and mineral oil + imidacloprid exhibited relatively lower efficacy compared to the aforementioned treatments but still achieved considerable reductions in the *A. aurantii* population. The combination of mineral oil with insect growth regulators like buprofezin has been reported to disrupt the development and molting processes of scale insects (Tena *et al.*, 2017; Verdú *et al.*, 2023). Similarly, the inclusion of neonicotinoid insecticides like Imidacloprid has been shown to enhance the penetration and systemic activity of mineral oil, contributing to improved pest control (Hidalgo *et al.*, 2019; Pekas *et al.*, 2022).

Notably, the percentage reductions generally increased over time across all treatments and tree levels, indicating the progressive effectiveness of the insecticidal applications. This trend aligns with previous studies that have observed a delayed response in scale insect mortality due to the protective waxy coverings and sedentary nature of these pests (Bouaguen *et al.*, 2018; Atli *et al.*, 2022).The observed variations in efficacy among the different treatments and tree levels can be attributed to factors such as the mode of action of the active ingredients, their penetration and distribution within the plant, and the microhabitat preferences of *A. aurantii* at different tree levels (Hidalgo *et al.*, 2019; Verdú *et al.*, 2023).It is crucial to consider the potential environmental and ecological implications associated with the use of insecticides. While the integration of mineral oil with selective insecticides may mitigate some risks, continuous monitoring and responsible application practices are essential to minimize adverse effects on non-target organisms and promote sustainable pest management strategies (Urbaneja *et al.*, 2020; Bouvet *et al.*, 2021).

Future research should explore the long-term efficacy and residual effects of these integrated treatments, as well as their compatibility with other biological control agents and cultural practices. Additionally, investigating the potential development of resistance in *A. aurantii* populations to these insecticidal combinations is crucial for maintaining their effectiveness over time (Karamaouna *et al.,* 2019; Pekas *et al.*, 2022).

Integrating chemical control methods with other sustainable practices, such as cultural and biological control strategies, can further enhance the overall effectiveness and environmental sustainability of *A. aurantii* management programs (Damos & Savopoulou-Soultani, 2022; Urbaneja *et al.,* 2020). The use of selective insecticides in combination with mineral oil can be complemented by the introduction of natural enemies, such as parasitoids and predators, to maintain long-term suppression of pest populations (Verdú *et al.,* 2023; Carvalho *et al.*, 2020).

Moreover, the implementation of precision agriculture techniques, including remote sensing and site-specific application of insecticides, can optimize resource utilization and minimize non-target impacts (Calderón *et al.,* 2022; Bouvet *et al.,* 2021). Ongoing monitoring and adaptation of management strategies based on environmental conditions, pest population dynamics, and resistance development are crucial for maintaining the efficacy of these integrated approaches (Pekas *et al.,* 2022; Karamaouna *et al.,* 2019).
Recent advances in precision agriculture and remote sensing technologies offer promising avenues for integrating meteorological data and pest monitoring systems, enabling more effective and sustainable pest management practices for *A. aurantii* in orang orchards (Calderón *et al.*, 2022; Samietz *et al.,* 2022; Jacas & Urbaneja, 2010; Bouvet *et al.,* 2021; Atli *et al.*, 2022).

Conclusion:

The findings of this study demonstrate the potential of integrating mineral oil with selective insecticides as an effective strategy for managing *Aonidiella aurantii* populations in orange orchards. The mineral oil + Dimethoate and mineral oil + Chlorpyrifos-methyl treatments exhibited superior efficacy, consistently reducing pest populations across different tree levels and seasons. However, it is crucial to consider the potential environmental implications and resistance development associated with these insecticidal treatments. Future research should focus on exploring long-term efficacy, compatibility with biological control agents, and the development of resistance management strategies. By incorporating these integrated approaches into comprehensive pest management programs, orange growers can effectively control *A. aurantii* while promoting sustainable and environmentally responsible practices in orang production.

Declarations:

Ethics Statement: This study was conducted in compliance with all applicable ethical standards and regulations. No human participants or vertebrate animals were involved in this research.

Authors Contributions: Ayman S. Gaber, from Al-Azhar University, Assiut Branch, conceived and designed the study, supervised the project, and led the data analysis and interpretation. Ahmed T. H. Ghanem, from Al-Azhar University, Assiut Branch, conducted the field experiments, collected the data, and contributed to data analysis. Mahmoud Abbas Ali, from South Valley University, provided expertise in pest management, assisted in designing the experiments, conducted data analysis, and generated graphs for the manuscript. All authors reviewed and approved the final manuscript and agree with its submission to the *Egyptian Academic Journal of Biological Sciences A. Entomology.*

Conflict of Interest: The authors declare no conflict of interest**.**

Availability of Data and Materials: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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