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Functional Groups Of Parasitoid Hymenoptera As Key Agents In Sustainable Citrus Pest Management In Algeria

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Abstract
Biological control provided by parasitoid Hymenoptera represents a cornerstone of natural pest regulation in citrus agroecosystems, complementing the essential pollination services that sustain agricultural productivity. Despite their ecological and economic importance, the functional structuring of parasitoid communities in orchards remains insufficiently explored. This study investigates the diversity and behavior of auxiliary hymenopteran functional groups associated with citrus orchards in Central Mitidja, Algeria, with the aim of assessing their potential contribution to integrated pest management (IPM). Our analyses highlight that parasitoid diversity is not solely determined by species richness, but rather by functional diversity and the differentiated roles species play within communities. NMDS analyses reveal that dominant species (Encarsia sp., Aphidius sp., Aphelinusmali) exert a structuring influence, while less abundant taxa can nonetheless provide significant functional contributions(Alloxysta sp.). Ecological indices further demonstrate the impact of phytosanitary practices on parasitoid community organization, underscoring the detrimental effects of intensive insecticide use on beneficial insect populations. The findings emphasize that conserving high functional diversity is critical for maintaining ecosystem services, particularly natural pest regulation. By deepening understanding of parasitoid functional groups, this research supports the development of sustainable IPM strategies that preserve natural enemies, reduce reliance on chemical inputs, and enhance the resilience of citrus-growing systems.

Keywords: Parasitoid Hymenoptera, Functional Diversity, Integrated Pest Management (IPM), Citrus Agroecosystems, Biological Control

1. INTRODUCTION

Biological control, particularly that provided by Hymenoptera, plays a crucial role in the natural regulation of pests, while crop pollination by beneficial insects remains indispensable for sustaining agricultural productivityrepresenting an economic value of several millions dollars annually. Arboriculture is an important economic sector that benefits from these ecosystem services. The functional structuring of parasitoid communities, which deliver multiple ecosystem services, has been relatively understudied in orchards (McCravy, Clem, Bailey, Elgar, &Blaauw, 2024; Khaladi et al., 2025).

Monzó and Stansly (2020) emphasize that an agroecosystem lacking an effective conservation biological control program for suppressing the Asian citrus psyllid would incur projected economic losses ranging from $1,150 to $2,000 per hectare. These findings highlight the commitment to identifying a definitive and sustainable solution to citrus diseases and pests. Moreover, they provide valuable insights for optimizing mass-rearing protocols and enhancing the efficiency of natural enemies in biological control applications (Zhang et al., 2025).

In order to preserve beneficial insects and maximize the biological control services they provide, it is important to recognize that numerous pest species pose devastating threats to the citrus economy. This situation necessitates the implementation of intensive insecticide programs against these species for the management of bio-aggressors, aimed at reducing the infestation of infected treesthough with unknown side effects on communities of natural enemies and the beneficial arthropod fauna of citrus agroecosystems (Monzo, Qureshi, &Stansly, 2014). Monthly insecticide sprays in citrus orchards have negatively affected populations of natural enemies, leading to reduced activity, particularly during the critical growth period of late winter and early spring. Consequently, pest populations exhibited the highest growth rates in areas where insecticides had detrimental effects on natural enemies (Monzo&Stansly, 2017).

Moreover, although chemical control methods may provide immediate solutions, their impact is often highly detrimental to ecological balance through the reduction of beneficial insect populations (Camerini, Maini, &Limonta, 2024; Gómez-Guzmán& González-Ruiz, 2019; Samanta et al., 2023). In contrast, conservation biological control supports integrated pest management programs in citrus-growing regions, where producers apply either broad-spectrum or selective insecticides (Monzo&Stansly, 2020).

Núñez-Campero et al. (2025) demonstrated that estimating the functional response allowed for the comparison of models across four neotropical parasitoid species associated with A. fraterculus: the pupal parasitoid Copterahaywardi and the larval parasitoids Ganaspispelleranoi, Doryctobraconcrawfordi, and Opiusbellus. The results revealed that G. pelleranoi and C. haywardi were highly effective in host utilization, in terms of attack rates and host rejection, thereby contributing to greater stability of the host–parasitoid system. Consequently, these two parasitoids are potential biocontrol agents in programs employing the strategy of augmentative biological control.

Escobero et al. (2025) reported that, based on functional traits reflecting the capacity of species to adapt to changing environments, the relationship between abundance and functional traits along a landscape heterogeneity gradient influences hymenopteran groups in terms of their abundance. Increased landscape heterogeneity favored the abundance of social hymenopterans compared to solitary ones. Moreover, greater landscape heterogeneity enhanced the abundance of small- and medium-sized hymenopterans.

Khaladi et al. (2025) asserted that the abundance of auxiliary hymenopterans varies according to the developmental stages of the tree. However, understanding the biodiversity of egg parasitoids in an agroecosystem is crucial for their conservation and integration into potential integrated pest management programs. The Trichogrammatidae provide new insights into the evolution of parasitoid diversity and improve the use of hymenopteran parasitoids in biological control (Sheng et al., 2025). Furthermore, Pintureau (2012) noted that several families, not only the Trichogrammatidae, can host these parasitoids.

The parasitoid activity of Aphytismelinus and Comperiellabifasciata has proven crucial for regulating populations of Aonidiellaaurantii. This study underscores the importance of conserving natural enemies in the implementation of integrated pest management strategies, while maintaining the ecological balance of citrus orchards. When necessary, insecticide sprays compatible with conservation auxiliaries may be applied (Najjar&Boulahia-Kheder, 2025).

According to Correa et al. (2016), biological control of armored scale insects requires the identification of their parasitoids in order to evaluate their potential as biocontrol agents. All identified parasitoids belong to the family Aphelinidae (Hymenoptera) and include five species of Aphytis (including A. melinus), four species of Encarsia (some of which remain unidentified), and one species of Ablerus (a hyperparasitoid). EncarsiainquirendaSilvestri, 1930 and an unidentified Encarsia were the only taxa capable of parasitizing both subfamilies (Aspidiotinae and Diaspidinae).

The family Aphelinidae currently comprises 37 genera and approximately 1,500 species, many of which are parasitoidsthough this figure likely underestimates their true diversity. For this reason, emphasis must be placed on the recognition, morphology, systematics, biology, genomics, and economic importance of this functional group as biocontrol agents (Polaszek, Kresslein, &Lahey, 2025).

Augmentative biological control promotes sustainable food production by reducing dependence on chemical insecticides. The Aphytis group is the principal natural enemy of scale pests; this genus of parasitoids is primarily used for its effectiveness in regulating scale insect populations. Evaluation of the biological characteristics of Aphytis spp. and their parasitic potential suggests that optimized production of Aphytis individuals improves profitability for growers and contributes to the sustainability of agroecosystems by reducing reliance on chemical insecticides (García et al., 2025).

The objective of our study is to deepen understanding of the behavior of auxiliary hymenopteran functional groups with potential to regulate pest populations. This contributes to the development of more sustainable and relevant methods for integrated pest management in citrus-growing regions.

2. MATERIALS AND METHODS

2.1. Study Area

The study was conducted during April and May 2019 in a citrus orchard located in the Mitidja-Center region, the largest sub-littoral plain of Algeria, situated 30 km south of Algiers (36°57′56.29″ N, 3°07′30.18″ E) (Mutin, 1974). The orchard is characterized by a planting density of 666 trees per hectare over an area of 7 hectares.

The Mitidja region is subject to a Mediterranean climate and falls within a subhumid to semi-arid bioclimatic zone, marked by two distinct seasons: a humid season with mild, wet winters extending from November to April, and a hot, dry season lasting from May to October(Drouiche, Nezzal, &Djema, 2019). During our observations, average temperatures in April did not exceed 18 °C, while May was distinguished by the onset of rising temperatures, with an increase of approximately 3.5 °C. Recorded humidity levels during the study period ranged between 65% and 95%, whereas precipitation values were among the lowest observed, not exceeding 68.19 mm of rainfall. Climatic data used in this study were obtained from the NASA POWER website (https://power.larc.nasa.gov/data-accessviewer/).

2.2. Sampling and identification

Yellow sticky traps (10 × 25 cm) were placed on trees at a height of 1.60 m, avoiding orchard hedgerows bordered by windbreak trees, where the abundance of hymenopterans is typically lower. It is important to adapt inventory methods for hymenopterans (Baldy &Rabasse, 1983), given differences in insect behavior and ecological characteristics. The choice of this method is justified by its proven effectiveness for sampling flying hymenopterans in tree-based agroecosystems (Larsen et al., 2014). Recognized for its cost-effectiveness, this method offers simplicity of implementation, biological efficiency, and utility for long-term orchard monitoring (Daniel &Ramaraju, 2017; De Souza Da Silva et al., 2016; Drouiche et al., 2019; Larsen et al., 2014; Romeis et al., 1998; Shweta &Rajmohana, 2016, 2018; Wells & Decker, 2006).

Sampling of the studied insects was conducted in three 1-hectare blocks randomly selected within the overall orchard area. To ensure homogeneous and representative spatial coverage, three traps per hectare were deployed, minimizing disturbances and logistical constraints. During April and May 2019, traps were collected three times per week and replaced weekly (McCravy, 2018). The choice of this sampling period was based on the BBCH scale, in order to synchronize hymenopteran surveys with the first sap flow, a stage conducive to intensified plant activity and associated insect dynamics (Agustí et al., 1995). The orchard belonged to a private grower who applied treatments against various pests and diseases.

For identification of specimens captured at the study site, different guides and taxonomic keys were consulted to select families likely to contain parasitoid hymenopterans. Genera of each family were identified with reference to: Yefremova&Yegorenkova (2009) for the family Eulophidae; Delvare&Aberlenc (1989), Goulet & Huber (1993), Pintureau (2012), and Hayat (1983) for the family Aphelinidae; Beardsley & Huber (2000), Huber & Noyes (2013), Triapitsyn (2006), and Huber &Thuróczy (2018) for the family Mymaridae; Talamas, Masner, & Johnson (2011) and Talamas, Johnson, & Buffington (2015) for the family Scelionidae; and Querino& Zucchi (2005) for the family Trichogrammatidae. Essential orange oil was used to detach specimens from the sticky traps.

2.3. Statistical Analysis and Data Processing

The diversity of hymenopterans in each survey was estimated using the following non-parametric biodiversity indices:

- Species richness (S): Corresponds to the total number of insect species recorded at each site and across the entire study area (Magurran, 2004).
- Shannon diversity index (H′): Based on species abundance. (number of individuals, n_i), Shannon's diversity index was calculated using the formula:$H' = -\Sigma\ (pi \times \log_2 pi)$, où $pi = ni/N$ (Shannon & Weaver, 1949).
- Pielou's evenness index (J′): Calculated as$J' = H/Hmax$this measures the distribution of individuals among species. (Pielou, 1966).
- Simpson's dominance index (D) and its inverse (1/D): The larger the value of 1/D, the more balanced and diverse the community (Simpson, 1949).
- Chao1 richness estimator: Used to estimate potential species richness (Chao, 1984).
- Chao2 sampling completeness: Expressed as the percentage of estimated species actually observed (Chao, 1987).

- Jackknife 1 sampling completeness: Percentage of estimated species actually observed (Burnham & Overton, 1978).
- Bootstrap estimator: Provides an estimate of total species richness (Smith & van Belle, 1984).
- Sampling completeness: Expressed as the percentage of observed species relative to estimated richness, following Colwell &Coddington (1994).

To visualize similarities among hymenopteran communities in an ordered manner, a Non-metric Multidimensional Scaling (NMDS) analysis was performed (Legendre & Legendre, 2012). ANOSIM (Analysis of Similarities) was employed to statistically test significant differences among hymenopteran species groups (Clarke, 1993). Thus, similarity and dissimilarity among auxiliary insect communities were assessed using Bray–Curtis indices (Bray & Curtis, 1957).All statistical analyses were performed using the R software environment (R Core Team, 2025).

3. RESULTS

- **Abundance of Hymenoptera Species Recorded in the Study Orchard**

At the end of six surveys conducted in the study orchard, 28 species were recorded, representing a total of 2,009 individuals. With the exception of Cynipidae, 27 taxa were parasitoids belonging to 14 families of the order Hymenoptera. The relative abundance of each species was calculated and is summarized in Table 1.

Comparison of species richness across surveys revealed variation ranging from 19 to 26 species, while abundance fluctuated between 109 and 748 individuals. This pattern highlights the apparent dominance of certain groups by a few species, whereas others exhibited more balanced distributions.

Considering the high relative abundance values of the species recorded, the predominant taxa belonged to the family Aphelinidae—specifically Encarsia sp., Aphelinusmali, and Aphytismelinus. These species contributed significantly to the formation of the functional group during the study period, underscoring their central role in structuring the community. In addition, the family Scelionidae, represented by Scelionidae sp., was consistently observed with notable relative abundance values, emphasizing its ecological relevance and remarkable biotic potential.

A second group comprised species with intermediate abundance values compared to other taxa in each survey, including *Anagrus sp., Braconidae sp., Platygastridae sp., Aphidius sp., Ceraphronidae sp., Alaptus sp., and Megaspilidae sp.*

Table 1. Abundance of hymenopteran species present in the study orchard during the different surveys

Familly	Gender and species	Relative abundance (%)					
		Survey 1	Survey 2	Survey 3	Survey 4	Survey 5	Survey 6
Eulophidae	*Eulophidae sp.*	0,38%	0,13%	0,00%	0,00%	8,26%	1,24%
	Citrostichusphyllocnistoides	0,00%	0,13%	0,22%	0,00%	0,00%	0,00%
Encyrtidae	*Metaphycusflavus*	0,00%	0,00%	1,53%	0,00%	2,75%	2,49%
Aphelinidae	*Calesnoaki*	7,60%	4,81%	2,19%	3,70%	0,92%	2,90%
	Aphytismelinus	5,32%	0,67%	0,00%	1,59%	5,50%	6,64%
	Encarsiasp	50,19%	57,09%	42,23%	4,76%	5,50%	9,13%
	Aphelinusmali	1,14%	1,87%	3,06%	4,76%	10,09%	6,64%
	Aphytishispanicus	2,28%	5,88%	1,97%	2,65%	0,00%	9,54%
Pteromalidae	*Pteromalidaesp*	0,38%	0,53%	1,97%	1,59%	0,00%	0,41%
	Pachyneuronsp	0,76%	0,13%	0,00%	1,59%	2,75%	3,32%
Trichogrammatidae	*Trichogrammatidaespp*	0,00%	0,00%	2,63%	0,00%	0,00%	0,00%
Mymaridae	*Mymaridaesp*	0,38%	0,27%	1,97%	4,76%	0,00%	0,00%
	Gonatocerussp	0,00%	0,13%	0,00%	0,00%	11,93%	3,73%
	Comptopterasp	0,00%	0,40%	0,88%	2,12%	0,00%	1,24%
	Platystethyniumtriclavatum	0,76%	0,13%	0,44%	1,06%	0,92%	0,00%
	Alaptussp	1,52%	6,28%	6,35%	5,29%	0,92%	2,90%
	Anagrussp	2,28%	1,47%	3,50%	4,76%	5,50%	6,22%

Cynipidae	*Cynipidaesp*	1,52%	0,13%	0,00%	0,00%	0,92%	1,24%
Figitidae	*Phaenoglyphisvillosa*	0,00%	0,27%	0,44%	1,06%	0,00%	0,00%
	Alloxystasp	0,00%	2,94%	0,00%	0,00%	0,00%	0,00%
Scelionidae	*Scelionidaespp*	11,79%	4,95%	12,25%	12,17%	9,17%	6,64%
Platygastridae	*Platygastridaesp*	2,66%	0,40%	4,16%	10,05%	2,75%	19,50%
Ichneumonidae	*Ichneumonidaesp*	0,76%	1,87%	0,88%	3,70%	0,92%	3,32%
Braconidae	*Braconidaesp*	3,80%	3,21%	7,66%	6,88%	16,51%	4,15%
	Aphidiussp	3,04%	3,21%	0,88%	5,82%	1,83%	0,41%
	Lysiphlebusfabarum	0,00%	0,53%	2,19%	5,29%	0,00%	0,00%
Ceraphronidae	*Ceraphronidaesp*	1,52%	1,47%	0,22%	10,58%	5,50%	7,05%
Megaspilidae	*Megaspilidaesp*	1,90%	1,07%	2,41%	5,82%	7,34%	1,24%

Diversity Indices in the Study Orchard and Estimation of Species Richness

The diversity indices revealed that certain samples exhibited high diversity with a homogeneous distribution of abundances (H' > 2.6; J' > 0.88), in contrast to others that were characterized by strong species dominance (H' = 1.82; J' = 0.56) (Table 2).

Table 2: Basic Diversity Indices per Survey

Survey	S_obs	N	H'	D	1/D	J'	Chao1	% Complete
survey1	20	263	1,942	0,72	3,572	0,648	21,5	93,023
survey2	26	748	1,82	0,658	2,921	0,559	35	74,286
survey3	23	458	2,208	0,79	4,759	0,704	25,25	91,089
survey4	22	190	2,864	0,934	15,042	0,927	22,25	98,876
survey5	19	109	2,623	0,913	11,435	0,891	31,5	60,317
survey6	21	241	2,704	0,914	11,651	0,888	22	95,455

Observed Species Richness and Diversity Indices in the Study Orchard

The observed species richness (S_obs) ranged from 19 species (survey 5) to 26 species (survey 2), indicating moderate heterogeneity in species composition among the surveys. The total number of individuals (N) varied considerably, with a maximum in survey 2 (748 individuals) and a minimum in survey 5 (109 individuals), reflecting differences in abundance likely influenced by local or temporal conditions.

The Shannon diversity index (H′) ranged from 1.82 (survey 2) to 2.864 (survey 4). The highest values, observed in surveys 4, 6, and 5, indicate more diverse communities, combining relatively high species richness with a more balanced distribution of abundances.

The Simpson dominance index (D) ranged from 0.658 to 0.934. High values of D (surveys 4, 5, and 6) suggest low dominance by one or a few species, and thus a more balanced community structure. In contrast, survey 2 showed the lowest D value, suggesting notable dominance by certain species despite relatively high species richness.

The reciprocal Simpson index (1/D) confirmed this trend, with much higher values for survey 4 (15.042) and survey 6 (11.651), indicating substantial actual diversity.

Pielou's evenness index (J′) ranged from 0.559 (survey 2) to 0.927 (survey 4). High values observed in surveys 4, 5, and 6 reflect a more homogeneous distribution of individuals among species, whereas the low evenness in survey 2 indicates a dominated community structure.

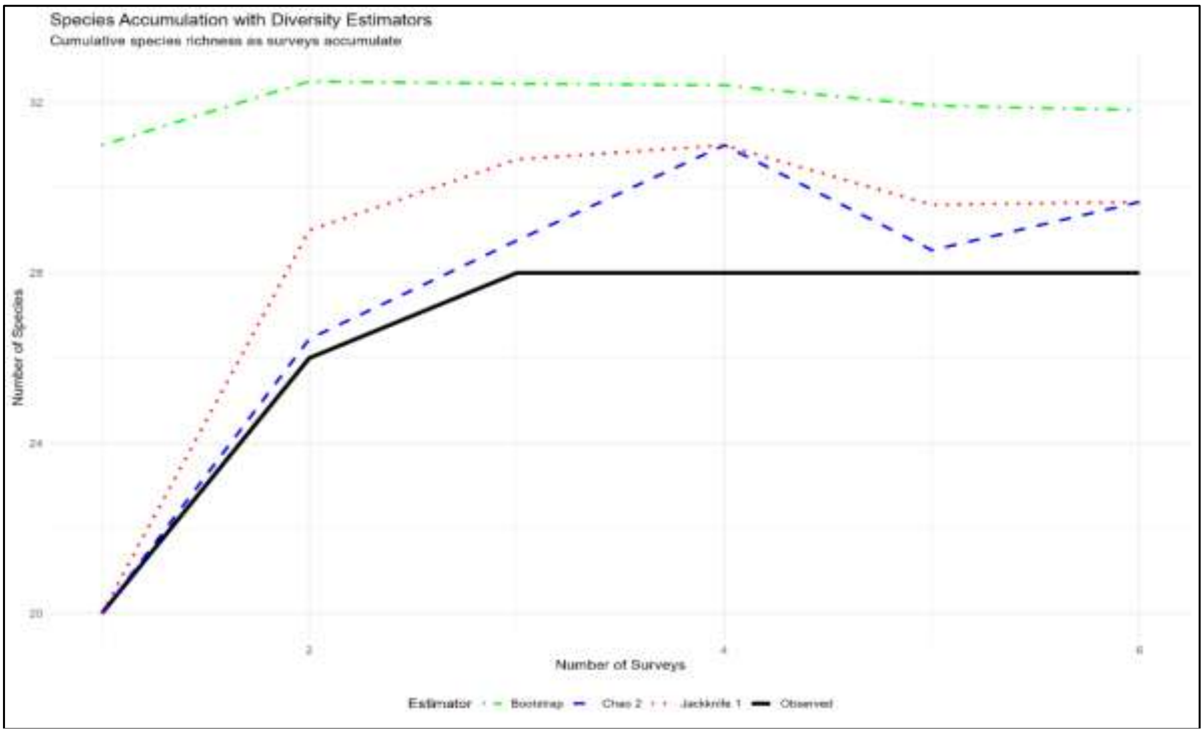

Figure 1. Species accumulation curve with non-parametric diversity estimators.

The NMDS ordination provided a synthetic and reliable representation of the composition of auxiliary insect communities (stress = 0.067). The low stress value (<0.1) indicates that the spatial configuration of the points accurately reflects the similarities and dissimilarities among surveys. Axes 1 and 2 allowed the distinction of survey groupings based on the specific composition of primary parasitoids, hyperparasitoids, and other taxa.

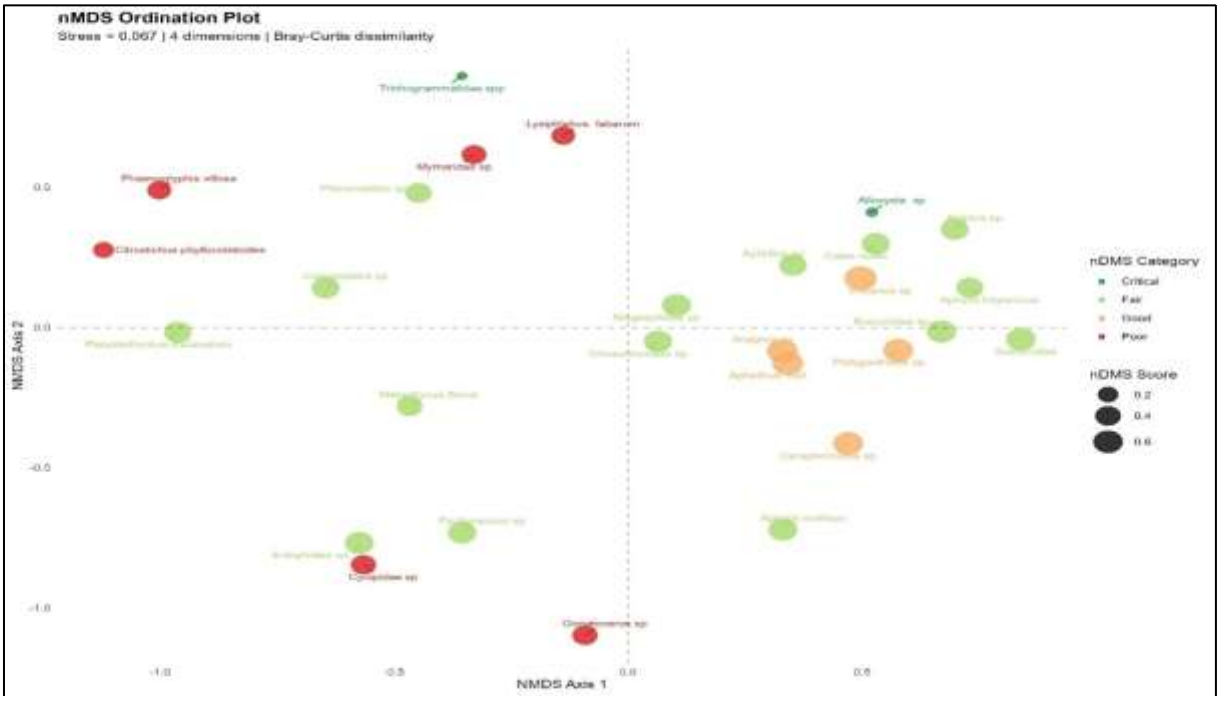

Figure 2. nMDS ordination of parasitoid communities based on Bray–Curtis dissimilarity (stress = 0.067).

Two-Dimensional NMDS Ordination (NMDS1–NMDS2)

The two-dimensional NMDS ordination (NMDS1–NMDS2), based on Bray–Curtis distance, revealed a partial structuring of the parasitoid Hymenoptera community, with a low stress value (stress = 0.067), indicating an excellent representation of functional compositional dissimilarities among surveys. This structuring was statistically confirmed by ANOSIM (R = 0.25; p = 0.006), demonstrating a significant yet moderate differentiation among the observed assemblages.

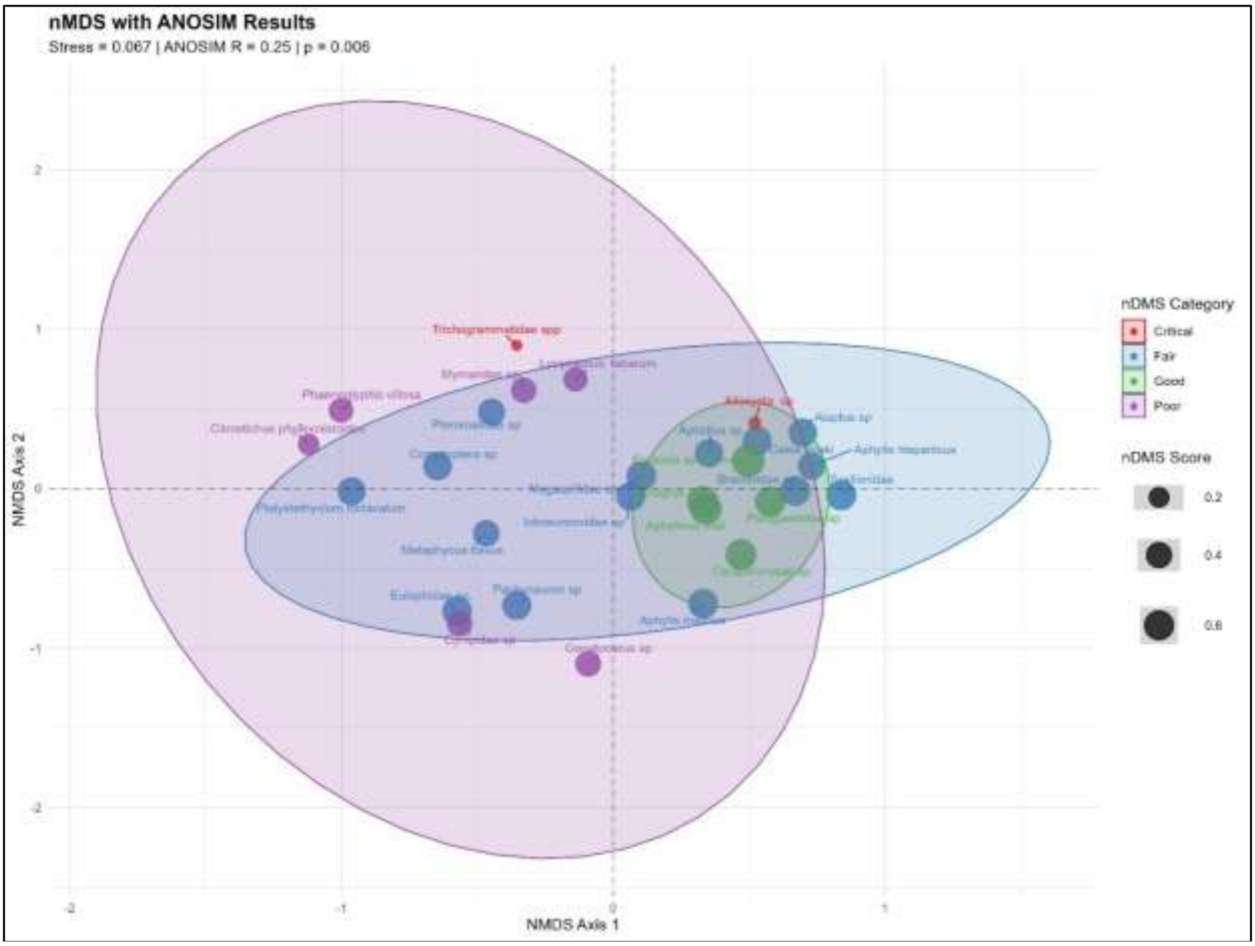

Figure 3. nMDS ordination (axes 1–2) based on Bray–Curtis dissimilarity. ANOSIM: R = 0.25; p = 0.006; stress = 0.067. Points represent identified taxa, with symbol size corresponding to NMDS scores and colors indicating functional performance categories.

4. DISCUSSION

- **Diversity of ParasitoidHymenoptera**

The diversity indices revealed notable differences among surveys, with survey 4 showing the highest diversity, evenness, and sampling completeness. In contrast, survey 2, despite its high species richness, exhibited lower evenness and higher dominance, suggesting an imbalanced community structure. Daniel et al. (2019) demonstrated that parasitoids are highly sensitive to habitat changes, while Mateos et al. (2011) added that their taxonomic and functional response to fire was explained by the number of parasitoids being positively correlated with the abundance of potential arthropod hosts. Escobero et al. (2025) reported that landscape heterogeneity strongly influences parasitoid Hymenoptera abundance, with increases in heterogeneity favoring small- and medium-sized species. This aligns with previous studies showing that smaller species are more affected by landscape disturbances. Radrigán-Navarro and Fuentes-Contreras (2024) noted that buprofezin and pyriproxyfen are more compatible with A. flavidulus than acetamiprid, which can only be integrated into parasitoid activity if field residue levels remain low.

- **Functional Structuring of Parasitoid Communities**

The moderate ANOSIM R value (R = 0.25) combined with high significance suggests a functional gradient among parasitoid communities rather than a strict separation, reflected in partial overlap of points in NMDS space. The NMDS ordination highlights marked functional structuring, with survey distributions reflecting differences in assemblage composition beyond simple taxonomic variation. Analysis of NMDS scores (Figures 2 and 3) shows that even low-abundance species can play important functional roles. Alloxysta sp., though rare, displayed a notable NMDS score, suggesting significant influence on community dynamics through its role as a hyperparasitoid.

Taxa occupying extreme NMDS positions, such as Encarsia sp., Aphidius sp., Aphelinusmali, and Alloxysta sp., contributed strongly to ordination structuring and reflected differential responses to orchard management conditions. Dominant species acted as keystone regulators of host populations, contributing to overall system stability. The coexistence of dominant, secondary, and rare species revealed a hierarchical functional organization typical of low-disturbance agroecosystems. Species of the genus Encarsia were significantly distinct from other groups, dominating surveys coinciding with high relative humidity and temperatures between 16–20 °C (Figure 4).

These species largely belong to primary parasitoids exploiting common hosts such as aphids and scale insects. Melone et al. (2025) emphasized that preserving parasitoid complexity within IPM programs could effectively control pest hosts in citrus orchards. Drobnjaković et al. (2025) studied the side effects of spinetoram, a semi-synthetic insecticide, on the whitefly parasitoid Encarsiaformosa, and found that spinetoram significantly reduced its effectiveness when applied at recommended field doses.

- **Contribution of Key and Rare Species to Functional Diversity**

NMDS scores showed that functional contributions of species were not strictly proportional to their abundance. Rare species such as Alloxysta sp. made notable functional contributions despite low frequency, suggesting indirect but important roles likely linked to higher-level trophic interactions.

The NMDS ordination (stress = 0.067) provided a reliable low-dimensional representation of community composition. ANOSIM detected significant differences among management categories (R = 0.25; p = 0.006), indicating moderate but significant separation of assemblages. A relatively compact cluster formed by dominant functional group species contrasted with more dispersed groups, reflecting greater heterogeneity. The analysis suggests that several taxa (e.g., Trichogrammatidae spp., Alloxysta sp.; Figure 4) were associated with unfavorable conditions, while others (e.g., Aphidius sp., Aphelinusmali) characterized more favorable conditions.

Boivin (2010) also reported that economically important egg parasitoids belong to families such as Trichogrammatidae, Mymaridae, Eulophidae, Scelionidae, Aphelinidae, Encyrtidae, and Platygastridae. Understanding species responses to environmental disturbances is a key conservation objective, requiring monitoring through taxonomically and functionally diverse groups such as Hymenoptera (Daniel et al., 2019). Stathakis et al. (2023) recommended the use of aromatic plant species in conservation practices targeting beneficial arthropods in orange orchards, while also considering the role of appropriate wild flowering plants from the surrounding flora. Khaladi et al. (2025) studied egg parasitoid diversity in a northeastern Algerian citrus orchard and identified species of interest from families Aphelinidae, Scelionidae, Mymaridae, Trichogrammatidae, and Eulophidae, with abundances varying according to factors such as the absence of insecticide treatments.

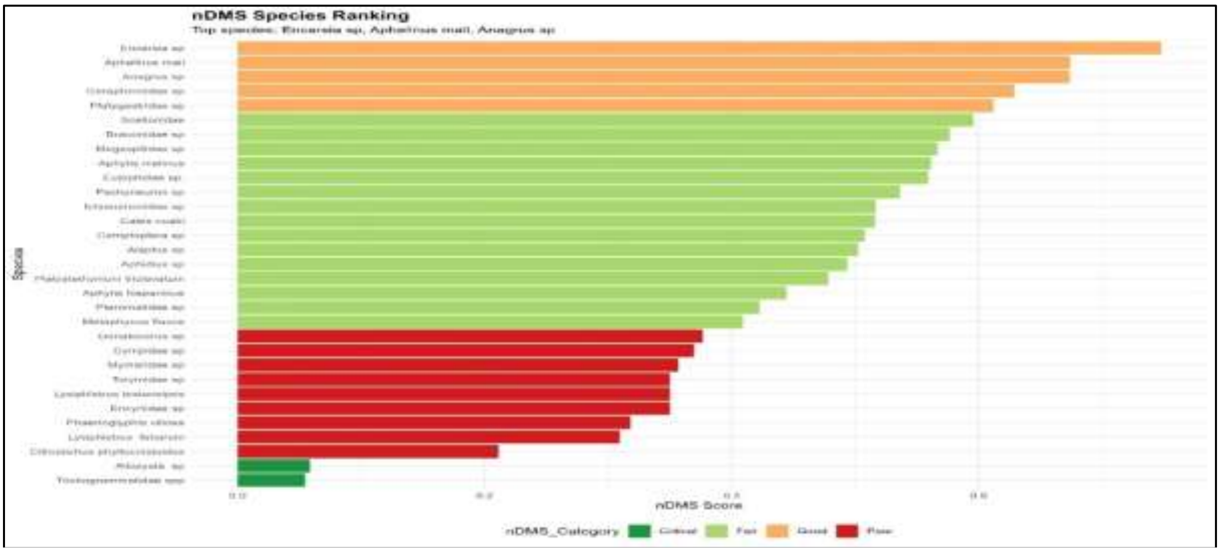

Figure 4. Ranking of parasitoid Hymenoptera according to nMDS scores, indicating their contribution to differences among assemblages.

5. CONCLUSION

This study demonstrates that the diversity of parasitoid Hymenoptera in citrus orchards depends not only on species richness but, more importantly, on functional diversity and the differentiated contributions of species to community functioning. NMDS analyses revealed that certain dominant species play a structuring role, while less abundant species can nonetheless exert significant functional influence. The various ecological indices observed in citrus orchards highlight the impact of phytosanitary practices on the functional organization of parasitoid communities. Conserving high functional diversity thus emerges as a key element for maintaining ecosystem services, particularly natural pest regulation. These findings reinforce the importance of adopting integrated management strategies that promote the preservation of natural enemies within agroecosystems.

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