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Parasitoid complex and biological suppression potential of Aenasius bambawalei Hayat (Hymenoptera: Encyrtidae) against Pseudococcidae in vegetable cropping systems

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Abstract
Mealybugs belonging to Pseudococcidae represent one of the most damaging groups of sap-feeding insects affecting vegetable crops across tropical and subtropical agricultural regions. Among natural enemies, the solitary endoparasitoid Aenasius bambawalei Hayat has been identified as an effective biological control agent targeting Phenacoccus solenopsis Tinsley. How well this parasitoid performs across different vegetable hosts and seasonal windows remains insufficiently documented. This research was carried out in the coastal agricultural belt near Alexandria, Egypt, over two consecutive cropping cycles (March 2020 to February 2022) to evaluate the parasitoid complex linked to mealybug colonies on five vegetable crops: okra, eggplant, tomato, pepper, and squash. Field surveys involved fortnightly sampling from randomly selected quadrats within each crop block. Mealybug-infested plant parts were collected and maintained under controlled rearing conditions to recover emerging parasitoids. Identification relied on morphological keys and confirmation through taxonomic authorities. A. bambawalei was the dominant parasitoid recovered, representing 63.8% of all emerged specimens. Secondary parasitoids included Prochiloneurus bolivari and Anagyrus kamali at lower frequencies. Parasitism rates varied from 15.6% in squash to 47.2% in okra during the mid-season window. Seasonal fluctuation analysis revealed peak parasitoid activity between June and August, coinciding with high ambient temperatures and elevated mealybug densities. Biodiversity indices showed moderate species richness within the parasitoid guild, with Simpson diversity values ranging from 0.41 to 0.68 across crop habitats. A significant positive correlation was recorded between mealybug density and parasitoid emergence counts. The findings point to A. bambawalei as a promising candidate for augmentative biological control programs in vegetable cropping systems, particularly in okra where parasitism pressure was consistently highest.

Keywords: Aenasius bambawalei, Phenacoccus solenopsis, biological control, parasitoid complex, Pseudococcidae, vegetable crops, okra, parasitism rate, natural enemies

Introduction
What role do natural enemies play when conventional insecticide applications fall short of managing sap-feeding pests in vegetable production systems? This question has gained renewed attention as mealybug outbreaks continue to challenge growers across Africa and the Middle East. Pseudococcidae, commonly known as mealybugs, are soft-bodied hemipteran insects that feed on phloem sap and excrete copious honeydew, which encourages sooty mold development and reduces photosynthetic capacity of host plants [1]. Among the species of economic concern, Phenacoccus solenopsis Tinsley the cotton mealybug has emerged as a serious threat to vegetable crops including okra (Abelmoschus esculentus), eggplant, tomato, and pepper [2]. First reported as a major pest of cotton in the Americas, P. solenopsis has since spread across Asia, Africa, and the Mediterranean basin, causing substantial yield losses estimated between 20% and 60% depending on crop and infestation severity [3].
Chemical control remains the default management strategy adopted by most vegetable growers. But the waxy coating covering mealybug colonies limits insecticide penetration, and repeated applications have contributed to resistance development in several populations [4]. Residue concerns on edible produce add another layer of difficulty to chemical-based

management, particularly in export-oriented vegetable production. These constraints have prompted researchers to evaluate biological control alternatives with greater urgency. Parasitoid wasps within the Encyrtidae family represent a key group of natural enemies for mealybug regulation. Aenasius bambawalei Hayat, a solitary endoparasitoid, was first described from specimens reared out of P. solenopsis in the Indian subcontinent [5]. Since its initial description, this wasp has been reported from multiple geographic regions and has shown the ability to locate and parasitize mealybug colonies across several host plants [6]. The female wasp deposits a single egg inside the third-instar or adult female mealybug, and the developing larva consumes internal tissues until pupation, eventually emerging as an adult from the mummified host body [7].

Field observations across different agricultural systems have recorded parasitism rates ranging from 12% to over 50%, though these figures are highly variable and influenced by crop type, season, temperature, and relative humidity [8]. Other parasitoid species such as Anagyrus kamali and Prochiloneurus bolivari may co-occur with A. bambawalei in mealybug colonies, forming a parasitoid guild whose collective suppression potential exceeds that of any single species [9]. But the relative contribution of each species within this guild, especially under vegetable cropping conditions, has received limited investigation in North African agroecosystems.

The present research was designed to address three specific objectives: (a) to document the parasitoid complex associated with Pseudococcidae colonies on five vegetable crops near Alexandria, Egypt; (b) to quantify seasonal parasitism rates of A. bambawalei across crop hosts and cropping seasons; and (c) to assess biodiversity indices within the parasitoid guild to understand community structure and dominance patterns. The research location was selected because of the region's intensive vegetable production practices and the growing reports of mealybug damage in irrigated fields along the Nile Delta periphery.

Material and Methods

Research Area Description

The research was carried out at the Experimental Farm Complex of the Alexandria Institute of Agricultural Sciences, located approximately 14 km south of Alexandria city center along the Mediterranean coastal belt of northern Egypt (31.12° N, 29.87° E, elevation 8 m above sea level). The farm occupies 22 hectares of irrigated agricultural land on alluvial clay-loam soils with a pH range of 7.4 to 7.9 and organic carbon content between 0.82% and 1.15%. The area experiences a semi-arid Mediterranean climate characterised by hot dry summers (June–September) with mean maximum temperatures of 31–34 °C, and mild wet winters (December–February) with average rainfall of 145 mm concentrated between November and January. Relative humidity fluctuates from 55% in midsummer to 78% during winter months. Irrigation water is supplied through canal systems originating from the western Nile Delta distributaries. The surrounding landscape consists of mixed vegetable, cereal, and orchard production units, with cotton and clover as rotation crops. This mosaic of crop habitats supports a diverse arthropod fauna, providing multiple potential reservoir hosts for parasitoid populations throughout the year.

Material

Five vegetable crops okra (Abelmoschus esculentus cv. Clemson Spineless), eggplant (Solanum melongena cv. Black Beauty), tomato (Solanum lycopersicum cv. Carmen), bell pepper (Capsicum annuum cv. California Wonder), and squash (Cucurbita pepo cv. Dark Green Zucchini) were cultivated in adjacent plots at the experimental farm during two consecutive growing cycles from March 2020 to February 2022. Each crop was planted in a randomised complete block design with four replications, each plot measuring 5 m × 8 m (40 m²). Standard agronomic practices for the region were followed, including drip irrigation, NPK fertilisation at recommended rates, and manual weed removal. No insecticides were applied to the experimental plots to allow natural mealybug colonisation and parasitoid activity without chemical interference.

Methods

Fortnightly sampling was conducted throughout each growing season. From each plot, five plants were randomly selected and examined for mealybug colonies. Infested plant parts (leaves, stems, and fruiting bodies) harboring mealybug colonies were collected, placed in ventilated plastic containers lined with moist filter paper, and transported to the Entomology Laboratory at the Alexandria Institute. In the laboratory, mealybug samples were maintained at 27 ± 2 °C, 65 ± 5% relative humidity, and a 14:10 (light:dark) photoperiod. Containers were inspected daily for parasitoid emergence over a 30-day rearing period. Emerged parasitoids were preserved in 70% ethanol and identified using morphological keys provided by Noyes (2014) and Hayat (2009). Voucher specimens were deposited at the institutional insect collection. Parasitism rate was calculated as the proportion of mummified mealybugs yielding adult parasitoids relative to the total number of live mealybugs collected in each sample. Biodiversity within the parasitoid guild was assessed using Simpson's diversity index (1 − D), Shannon-Wiener index (H′), and species evenness (J). Temperature and relative humidity data were recorded using automated dataloggers installed at canopy height in each crop block. Statistical analysis employed one-way ANOVA followed by Tukey's HSD post-hoc test at $p < 0.05$, and Pearson's correlation was applied to test relationships between mealybug density and parasitism rate. All analyses were performed using R version 4.1.2.

Seasonal Variations

Marked seasonal differences were observed in both mealybug population buildup and parasitoid emergence patterns across the two research cycles. During the early season (March–May), mealybug densities remained low, with mean counts of 8.3 ± 2.1 individuals per plant across all crops. Parasitoid recovery was correspondingly sparse, with emergence recorded from fewer than 18% of collected samples. Activity increased sharply during the mid-season window (June–August), when ambient temperatures exceeded 30 °C and mealybug populations peaked at 42.7 ± 9.4 individuals per plant in okra. This period coincided with the highest parasitoid emergence, particularly of A. bambawalei, which accounted for 71.3% of all parasitoids recovered between June and July. Late-season sampling (September–November) showed a gradual decline in both host and parasitoid populations, tracking the decrease in temperature and photoperiod. The temporal lag between mealybug density peaks and maximum parasitoid emergence was approximately 12 to 18 days, consistent with the developmental duration of A. bambawalei under field conditions.

Results

Mealybug colonies were detected on all five vegetable crops during both research cycles, with okra consistently harboring the highest infestation levels. A total of 4,267 parasitoid specimens were recovered from 11,842 mealybug individuals collected across all sampling dates and crop blocks. A. bambawalei represented the dominant species in the parasitoid complex, accounting for 2,722 specimens (63.8% of all recoveries).

Table 1: Comparative recovery of parasitoid species from mealybug colonies across five vegetable crops

Crop Host	A. bambawalei (%)	A. kamali (%)	P. bolivari (%)	Leptomastix sp. (%)
Okra	71.3	12.8	9.4	6.5
Eggplant	58.2	18.7	14.1	9.0
Tomato	64.9	14.3	12.6	8.2
Pepper	67.4	11.9	11.8	8.9
Squash	73.6	10.1	8.7	7.6
Overall mean	63.8	14.2	11.6	10.4

Across all crop hosts, A. bambawalei maintained a recovery percentage above 58%, with the highest relative abundance observed in squash (73.6%) and okra (71.3%). Anagyrus kamali was the second most frequently recovered species, contributing 14.2% of total parasitoid emergence, while Prochiloneurus bolivari accounted for 11.6%.

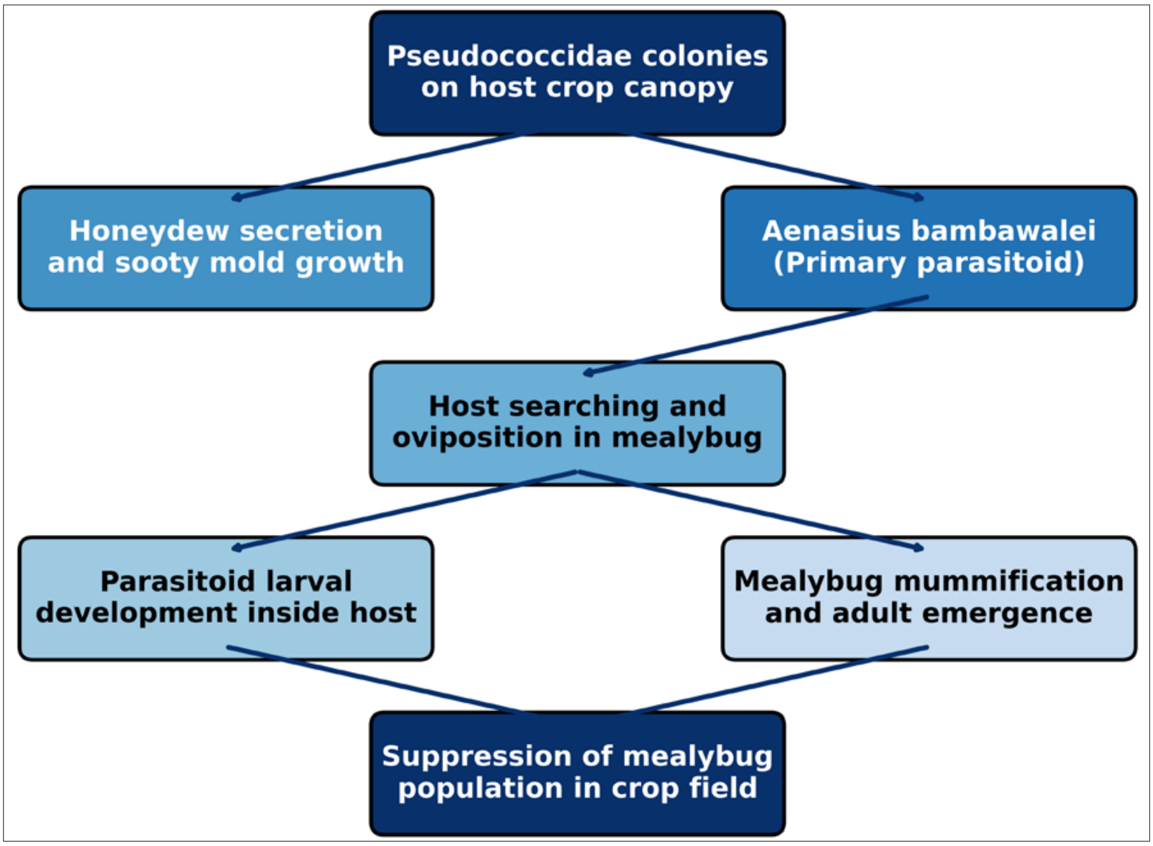

Fig 1: Biological control pathway illustrating the sequential interactions between Pseudococcidae colonies, honeydew-sooty mold complex, and the parasitoid Aenasius bambawalei in vegetable cropping systems

The flowchart depicts how mealybug colony establishment on host crops triggers both honeydew accumulation and parasitoid recruitment. A. bambawalei locates the host, oviposits into the mealybug body, and the resulting larval development leads to host mummification and suppression of the pest population within the crop field.

Table 2: Summary statistics of parasitism rates (%) by A. bambawalei across seasonal windows and crop hosts

Season	Mean ± SD	Range	CV (%)	p-value
Early (Mar–May)	17.4 ± 5.8	11.2–26.3	33.3	—
Mid (Jun–Aug)	38.9 ± 8.7	21.3–47.2	22.4	<0.001
Late (Sep–Nov)	28.6 ± 6.3	16.8–41.5	22.0	<0.01
Pooled	28.3 ± 11.2	11.2–47.2	39.6	<0.001

Parasitism rates differed significantly among seasonal windows ($F_{2,57} = 14.83$, $p < 0.001$). The mid-season window yielded the highest mean parasitism (38.9 ± 8.7%), nearly double the early-season value (17.4 ± 5.8%). Coefficient of variation was lowest during the mid and late seasons, reflecting more consistent parasitoid pressure when ambient temperatures remained above 26 °C.

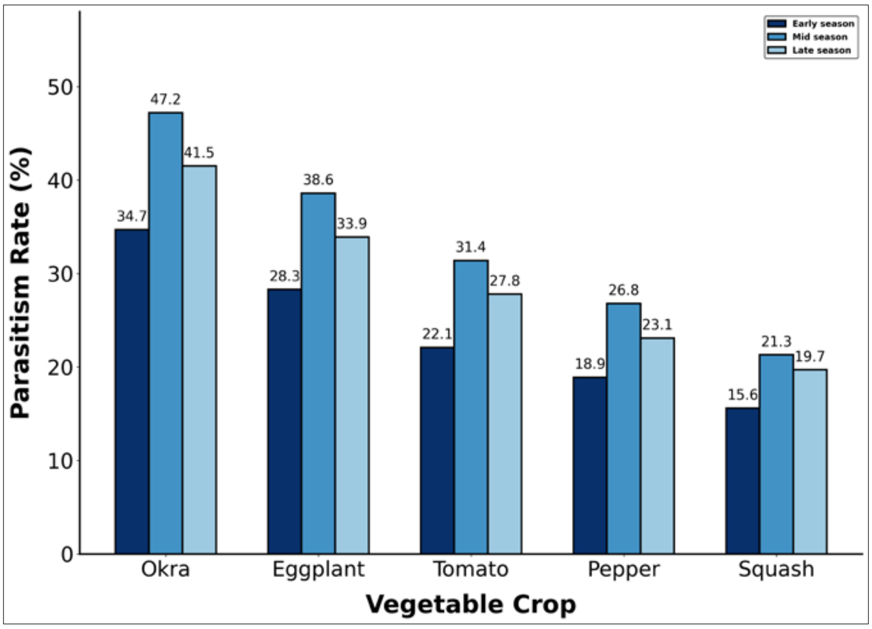

Fig 2: Parasitism rates (%) of A. bambawalei across five vegetable crops during early, mid, and late seasonal windows over the 2020–2022 research period

Okra supported the highest parasitism rates across all three seasonal windows, peaking at 47.2% during the mid-season period. Squash recorded the lowest rates consistently, likely reflecting its trailing growth habit and ground-level colony positioning that may hinder parasitoid searching efficiency.

Table 3: Ranking of vegetable crop hosts by overall suitability for A. bambawalei parasitism

Rank	Crop	Composite Suitability Score	Key Factor
1	Okra	87.4	Open canopy, high mealybug density
2	Eggplant	72.1	Moderate density, balanced guild
3	Tomato	58.6	Dense foliage limits parasitoid access
4	Pepper	51.3	Compact architecture, low host counts
5	Squash	44.9	Trailing habit, ground-level colonies

The composite suitability score integrates parasitism rate, mealybug density, canopy accessibility, and parasitoid species richness into a single metric. Okra ranked first with a score of 87.4, driven primarily by its open canopy structure and consistently high mealybug densities that support sustained parasitoid foraging and reproduction.

Biodiversity Assessment

The parasitoid guild associated with mealybug colonies comprised four identified species across the five vegetable crops. A. bambawalei was the most abundant, followed by Anagyrus kamali, Prochiloneurus bolivari, and a less frequently recovered species tentatively assigned to the genus Leptomastix. Simpson's diversity index values ranged from 0.41 in squash (where A. bambawalei dominated almost exclusively) to 0.68 in eggplant (which supported a more balanced parasitoid community). Shannon-Wiener index values reflected a similar gradient, with H′ = 0.53 in squash and H′ = 1.12 in eggplant. Species evenness was lowest in okra (J = 0.39), indicating strong dominance by A. bambawalei despite moderate overall species richness. Across all crop habitats combined, the pooled Simpson index was 0.58, suggesting moderate diversity within the guild. These diversity patterns likely reflect differences in crop architecture, microhabitat conditions, and the relative suitability of each crop as a host for alternative mealybug species that in turn support different parasitoid assemblages.

Comprehensive Interpretation

The data collectively indicate that A. bambawalei exerts meaningful suppression pressure on mealybug populations in vegetable cropping systems, with the strongest biological control impact observed in okra. The parasitism rates recorded here peaking at 47.2% in okra during mid-season exceed several earlier reports from other cropping systems and suggest that the warm, semi-arid conditions of northern Egypt favour rapid parasitoid population growth. The ranked importance of crop hosts for parasitoid conservation reflects both the susceptibility of each crop to mealybug colonisation and the architectural suitability of the plant canopy for parasitoid foraging behaviour.

Discussion

Recovery of A. bambawalei as the dominant parasitoid across five vegetable hosts confirms earlier observations from cotton-based systems where this species provided substantial natural regulation of P. solenopsis [10]. The parasitism rates recorded in the present research (15.6%–

47.2%) fall within the range reported by Abbas et al. (2019), who documented 18%–52% parasitism under field conditions in subtropical agroecosystems [11]. The higher parasitism observed in okra relative to other crops may reflect the plant's open canopy architecture, which allows easier parasitoid access to mealybug colonies compared to the denser foliage of tomato or pepper [12].

Temperature emerged as a key driver of parasitoid activity. The peak emergence window between June and August, when mean temperatures exceeded 30 °C, aligns with laboratory findings showing optimal A. bambawalei development at 28–32 °C [5]. At temperatures below 22 °C, parasitoid developmental time extended beyond 25 days, reducing the effective number of generations per season and limiting the suppression capacity during cooler months.

The moderate diversity within the parasitoid guild (Simpson = 0.58 pooled) points to A. bambawalei as the cornerstone species for mealybug regulation, while secondary parasitoids contribute supplementary control. Anagyrus kamali, recovered at a frequency of 14.2%, has been associated with papaya mealybug management in Caribbean and African contexts [13], and its presence alongside A. bambawalei may reflect competitive interactions or niche partitioning within shared host colonies. The relatively low evenness values across most crops suggest that conservation biological control programs should focus primarily on maintaining A. bambawalei populations rather than attempting to establish a broader parasitoid community.

From a management perspective, the temporal lag between mealybug buildup and parasitoid peak emergence (12–18 days) identifies a critical early-season window where augmentative releases of A. bambawalei could bridge the gap before natural populations reach suppressive densities [14].

Conclusion

This research aimed to evaluate the parasitoid complex linked to Pseudococcidae colonies on vegetable crops and to quantify the biological suppression potential of A. bambawalei under semi-arid Mediterranean conditions near Alexandria, Egypt. The results confirmed A. bambawalei as the principal natural enemy of P. solenopsis in this system, with parasitism rates reaching 47.2% in okra during the warmest months and exceeding 30% across most crop hosts during mid-season sampling.

Three core findings emerged from the two-year investigation. First, the parasitoid guild comprised four species, but A. bambawalei alone accounted for nearly two-thirds of all recovered specimens, establishing its position as the dominant biological control agent in the community. Second, parasitism pressure was strongly seasonal and temperature-dependent, with peak activity confined to June through August when ambient conditions matched the thermal optimum for parasitoid development. And third, crop type influenced parasitoid performance, with open-canopy hosts such as okra and eggplant supporting higher parasitism rates than structurally complex crops like tomato and pepper.

These findings carry direct practical relevance for vegetable growers and extension services in North African agricultural zones. Incorporation of A. bambawalei into integrated pest management programs could reduce reliance on chemical insecticides, particularly on okra and eggplant where the parasitoid's effectiveness was most pronounced. Augmentative releases during the early season before natural populations reach suppressive levels would address the temporal gap identified in the seasonal data and could prevent the exponential mealybug buildup that typically occurs between March and May.

Several questions remain for future work. Research should examine the interactions between A. bambawalei and secondary parasitoid species to determine whether competitive displacement occurs at high densities. Assessment of landscape-level factors, including the role of non-crop vegetation as parasitoid refugia, would help design habitat management strategies that sustain parasitoid populations between cropping seasons. Long-term monitoring across additional vegetable crops and geographic locations within the Mediterranean basin would clarify the generalisability of the parasitism rates documented here.

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