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Plant Spacing and Stand Density Effects on Aphid–Braconid Wasp Dynamics in Okra (Abelmoschus esculentus) in Benin City, Edo State

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Abstract
Aphid infestations represent a major constraint in okra production, yet their population dynamics are strongly influenced by crop configuration, growth stage, and prevailing weather conditions. Field experiment using a Randomized Complete Block Design (RCBD) was conducted to assess the effects of plant spacing and stand density on aphid abundance and associated parasitoid. Results indicated that plant spacing and stand density did not significantly ($p > 0.05$) affect aphid populations, although numerically higher infestations were observed under closer spacing (40 × 25 cm). In contrast, aphid abundance varied significantly across weeks after sowing (WAS), with populations remaining low at 2–3 WAS, rising sharply from 4–6 WAS, and peaking between 7–10 WAS. Pooled aphid populations across treatments reached maximum density (1202.00 individuals/five plants) at the 43rd meteorological week (8 WAS) while parasitoid populations peaked (14.50 individuals/five plants) earlier at the 39th week (4 WAS). Correlation analysis showed that aphid abundance was positively associated with temperature ($r = 0.86$) and parasitoid density ($r = 0.71$), but negatively correlated with humidity ($r = –0.75$) and rainfall ($r = –0.79$). Parasitoid abundance was significantly linked to aphid density but not to weather parameters, indicating a density-dependent response. These results underscore the importance of integrating crop growth stage, planting configuration, and climatic monitoring into pest management strategies for sustainable okra production.

Keywords: *Aphis gossypii*, Brachonid wasp, Okra production, Plant configuration, Weather parameters

1. Introduction

Okra (*Abelmoschus esculentus* L. Moench) is a widely cultivated vegetable in Nigeria and across West Africa (Uwiringiyimana *et al.*, 2024), valued for its nutritional, medicinal, and economic importance (Bawa and Badrie, 2016). Rich in vitamins, minerals, and mucilage, it serves as both a staple in local diets and a source of livelihood for smallholder farmers (Ibitoye *et al.*, 2022). The crop is predominantly grown by peasant farmers, either as a sole crop or intercropped, and is traditionally cultivated during the rainy season (Adeniyi, 2025). Despite its importance, okra productivity is significantly constrained by insect pests, with aphids being among the most destructive. *Aphis gossypii* Glover (Hemiptera: Aphididae) is recognized as a major pest of okra and other vegetables (Abang *et al.*, 2024). Aphids feed by extracting plant sap, which leads to chlorosis, stunted growth, and yield reduction (Shih *et al.*, 2023). More critically, they act as vectors of viral diseases, thereby compounding their economic impact (Gebretsadik *et al.*, 2025). Their rapid reproductive cycle enables populations to build up quickly under favourable conditions, especially in dense plantings where humidity and reduced airflow encourage pest proliferation (Van Emden and Harrington, 2017). Consequently, effective aphid management remains a priority in okra cultivation systems. Natural enemies, particularly parasitoid wasps from the family Braconidae, play a vital role in suppressing aphid populations by parasitizing and ultimately killing their hosts (Liu and Chen, 2025). However, their effectiveness is shaped by crop management practices, habitat structure, and host availability (Singh, 2023).

Agronomic practices such as plant spacing and stand density influence not only crop growth and yield but also pest–natural enemy dynamics. Wider spacing can reduce competition and potentially lower pest incidence, while dense stands may increase yield per unit area but favour aphid multiplication (Yusuf and Muhamman, 2020). Although spacing effects on crop yield have been widely studied, fewer investigations have examined how plant configuration alters the delicate tri-trophic balance between the host plant, aphid infestation, and parasitoid activity (Bastos *et al.*, 2020). Crucially, there is a distinct lack of empirical data on how structural canopy modifications—driven by stand density—impact the host-searching efficiency and temporal synchronization of indigenous Braconid wasps. Furthermore, standard agronomic spacing recommendations in Nigeria almost exclusively prioritize yield metrics, completely overlooking the inadvertent disruption or enhancement of native biological control ecosystem services. Understanding this ecological relationship is particularly significant in the humid tropical rainforest agro-ecology of Benin City, Edo State, where high ambient humidity and rainfall (Ofordu *et al.*, 2022) can alter both pest proliferation and parasitoid flight micro-climates.

This study therefore evaluates how plant spacing and stand density influence aphid infestation and braconid wasp dynamics in an okra cropping system in Benin City, Edo State. Serving as a specialized ecological companion to our previous work on the growth and yield metrics of these same systems (Omoregie and Mosali, 2026), this research bridges the gap between canopy architecture and tri-trophic ecological dynamics. The findings aim to establish a low-input cultural framework that optimizes indigenous biological control, thereby enhancing okra productivity and reducing smallholder dependence on hazardous chemical pesticides

2.0 Materials and methods

2.1 Experimental Site and Design

The field experiment was carried out during the late cropping season of September to November, 2024 at the Teaching and Research Farm of Department of Crop Science, Faculty of Agriculture, University of Benin, Benin city, Edo state, Nigeria. The geographical location of the experimental site is latitude 6˚23’59”N and longitude 5˚37’45”E with an elevation of 94.64 m. This location is characterized by a tropical climate. The soil type was sandy loam.

2.2 Experimental Design and Treatments

The experiment was laid as a Randomized Complete Block Design (RCBD) with six treatments and four replications (Blocks). There were six treatment combinations based on plant spacing and the number of plants per stand: 40 × 25 cm with one plant per stand (40 × 25 × 1), two plants per stand (40 × 25 × 2), three plants per stand (40 × 25 × 3), 50 × 25 cm with one plant per stand (50 × 25 × 1), two plants per stand (50 × 25 × 2), and three plants per stand (50 × 25 × 3). Each treatment plot measured 2 m × 2.5 m, and a spacing of 0.5 m was maintained between blocks and between plots.

2.3 Site preparation/Sowing/Fertilizer application and Weeding

A plot size measuring 18.5 m × 10.5 m field was cleared and manually ploughed. The local okra cultivar used was sourced from Ogan, Edo State. Seeds were sown after rainfall, six per hill, and thinned to the required number after three weeks. Urea fertilizer was applied at 60 kg/ha in three doses—two, four, and six weeks after sowing. Weeding occurred at two and six weeks after sowing. No chemical pesticide was applied during the study to allow natural aphid–parasitoid interactions to occur.

2.4 Data Collection

Data collection began from two to ten weeks after sowing (WAS). With the aid of hand lens, number of aphids and wasp parasitoids were recorded using direct visual counts. The counts were taken weekly from five (5) randomly selected plants within each treatment plot.

2.5 Collection of Meteorological Data

Weekly data on average temperature, relative humidity and total rainfall covering the period of study for Benin City, Edo State, were retrieved from the NASA Prediction of Worldwide Energy Resources (POWER) database and validated against the Nigerian Meteorological Agency (NiMet) 2024 Seasonal Climate Prediction (SCP) reports.

2.6 Data Analysis

Data from the experiment was subjected to square-root transformation prior to statistical analysis using One-way Analysis of Variance (ANOVA). Significant means ($p < 0.05$) were compared using Duncan’s New Multiple Range Test (DMRT). Pearson’s correlation analysis was used to assess relationships between aphid populations, predator abundance, and weather parameters. All analyses were done using GenStat version 12.1.

3.0 Result and Discussion

3.1 Effect of Plant Spacing and Stand Density on Aphid Abundance across WAS

Table 1 summarizes the effect of plant spacing and number of plants per stand on aphid abundance across weeks after sowing (WAS). Aphid abundance was not statistically different ($p > 0.05$) among the various plant spacing and stand densities, although numerically higher values were recorded under closer spacing (40 × 25 cm). This numerical trend suggests that canopy architecture modifies the localized microclimate; dense stands characteristically restrict airflow and elevate relative humidity, generating a boundary layer microenvironment that favours aphid colonization, settling, and survival in vegetable cropping systems (Van Emden and Harrington, 2017). This aligns with the observations of Omoregie and Ayefuwe (2026), who noted that while spatial configurations may not always yield statistically significant main effects on overall pest counts, denser configurations can under certain conditions foster microclimates conducive to pest colonization.

In contrast to the spatial treatments, aphid abundance showed marked temporal variation; with significant differences observed across WAS ($p < 0.05$). Populations remained minimal during the vegetative stage at 2-3 WAS, a seasonal onset pattern typical of *Aphis gossypii* initial establishment (Mahas *et al.* 2023). However, a sharp population increase occurred between 4 and 6 WAS. This surge was pronounced in the 40 × 25 × 1 treatment, with counts ranging from (112.50 individuals/ five plants at 4WAS to 189.50 individuals/ five plants at 6 WAS). Significant increases (69.50) was also recorded on 50 × 25 × 3 treatment at 4 WAS. The infestation progressed to distinct peaks across treatments during the mid-to-late growing stages: reaching maximum density in the 40 × 25 × 1 treatment at 8 WAS (220.00) and 9 WAS (216.20); in the 40 × 25 × 2 (338.00) and 50 × 25 × 2 (238.75) at 10 WAS; and in the 50 × 25 × 1 at 7 WAS (265.25). The 50 × 25 × 3 treatment recorded significant peaks at 8 WAS (103.50), 9 WAS (95.00) and 10 WAS (81.25). This rapid mid-season population explosion reflects the strong dependency of aphid reproduction on host plant phenology and nutritional quality. The sharp rise matches the onset of vigorous vegetative and early reproductive growth in okra, a phase characterized by an abundance of tender foliage and nutrient-rich phloem sap, which triggers exponential parthenogenetic reproduction (Hayashida *et al.*, 2026).

Similar developmental tracking has been reported by Shonga (2020) for *Brevicoryne brassicae* on brassicas, where low initial colonizing populations rapidly expanded alongside the host's foliar surface area. Furthermore, the late-season peaks observed under single-plant stands at closer spacing (40 × 25 × 1) reinforce the finding that plant configuration interacts dynamically with crop ontogeny. Denser spatial arrangements alter host-plant detectability and localized nutritional resource clusters, rendering single-plant configurations within tighter matrices highly susceptible to sustained pest loads as the crop matures (Omoregie and Ayefuwe 2026).

Table 1: Aphid abundance as influenced by plant spacing and number of plants per stand across weeks after sowing

	Treatments						
WAS	**40×25×1**	**40×25×2**	**40×25 ×3**	**50×25×1**	**50×25×2**	**50×25×3**	**Sig.**
2	0.70 (1.00)^{c}	0.00 (0.71)^{c}	1.20 (1.12)	0.25 (0.84)^{d}	4.75 (1.80)^{c}	0.00 (0.71)^{b}	ns
3	6.20 (2.27)^{bc}	33.00 (4.90)^{bc}	31.80 (4.32)	5.50 (1.96)^{d}	11.00 (2.59)^{bc}	4.00 (1.95)^{b}	ns
4	112.50 (10.20)^{a}	185.80 (12.71)^{ab}	67.00 (6.01)	25.25 (4.80)^{cd}	60.75 (7.79)^{abc}	69.50 (7.97)^{a}	ns
5	133.50 (11.44)^{a}	87.50 (9.02)^{ab}	115.50 (7.83)	79.75 (8.72)^{bc}	92.00 (9.56)^{ab}	53.75 (6.24)^{ab}	ns
6	189.50 (12.84)^{a}	157.00 (11.99)^{ab}	184.20 (12.32)	127.00 (11.15)^{ab}	73.00 (8.31)^{abc}	40.00 (6.31)^{ab}	ns
7	90.00 (9.07)^{ab}	123.50 (10.99)^{ab}	457.50 (15.43)	265.75 (15.95)^{a}	37.75 (5.64))^{bc}	57.75 (6.61)^{ab}	ns
8	220.00 (11.28)^{a}	163.50 (11.62)^{ab}	457.00 (17.93)	123.50 (10.46)^{b}	135.00 (9.38)^{ab}	103.50 (8.77)^{a}	ns
9	216.20 (12.01)^{a}	171.50 (12.41)^{ab}	235.00 (13.54)	97.50 (8.88)^{bc}	79.25 (8.06)^{abc}	95.00 (8.27)^{a}	ns
10	76.00 (8.29)^{ab}	338.00 (16.82)^{a}	177.20 (11.03)	94.75 (8.59)^{bc}	238.75 (12.97)^{a}	81.25 (8.12)^{a}	ns
Sig.	**	**	ns	***	*	*	

abcdMeans in the same column with different letter superscript are significantly different ((* = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$), ns = Means in the same row and column are not significantly different at $p > 0.05$. Means in parenthesis are square root transformed

3.2 Braconid Parasitoid Abundance as influenced by Plant Spacing and Stand Density

The effect of plant spacing and number of plants per stand on the abundance of associated braconid wasp parasitoid across WAS is shown in Table 2. The spatial treatments did not significantly influence parasitoid abundance ($p > 0.05$) during the majority of the sampling intervals, except at 10 WAS, where the 50 × 25 × 3 configuration recorded the highest count (0.75). Temporally, significant within-treatment variations across weeks ($p < 0.05$) were restricted to the 50 × 25 × 3 treatment, which reached a significant peak ($p < 0.05$) at 4 WAS (3.00 individuals/ five plants). In terms of overall seasonal progression, braconid wasps were scarce during the initial weeks (ranging from 0.00–0.25 at 2 WAS and 0.00–0.50 at 3 WAS), followed by a notable uniform increase at 4 WAS, led by the 40 × 25 × 1 (3.25) and 50 × 25 × 3 (3.00) treatments. Between 5 and 9 WAS, parasitoid population oscillated: maintaining moderate levels at 5 WAS, declining at 6 WAS, and subsequently peaking at 7 WAS within the 50 × 25 × 1 treatment (4.00) and at 8 WAS within the 40 × 25 × 1 treatment (5.75). A general population decline occurred across all treatments by 9–10 WAS.

The absolute scarcity of braconid wasps during the early vegetative weeks and their delayed population increase relative to aphid proliferation illustrates classic density-dependent numerical response dynamics. As specialized natural enemies, braconids require a critical baseline host density (Singh, 2023) to stimulate searching behaviour and sustain reproductive success. Consequently, their field abundance lags behind pest outbreaks, aggregating only after prey colonies have established sufficient biomass (Morgan *et al.*, 2017; Okuyama, 2024). The distinct early parasitoid peak at 4 WAS under the highest stand density (50 × 25 × 3) supports the premise that plant architecture and canopy density strongly mediate natural enemy activity (Horgan, 2017). The dense cluster of three plants per stand likely intensified localized aphid aggregation, creating a highly detectable chemical or physical cue that attracted foraging wasps. This corroborates findings by Lucatero *et al.* (2024) and Modu *et al.* (2024), who observed that structural modifications within the crop matrix alter natural enemy recruitment by concentrating host resources. Conversely, the subsequent parasitoid peaks observed at 7 and 8 WAS within single-plant stands (50 × 25 × 1 and 40 × 25 × 1 respectively) suggest a different structural mechanism during later crop growth stages. In less crowded, single-plant configurations, the reduction in architectural complexity likely enhanced the visual and olfactory host-searching efficiency of the braconids, facilitating easier host detection once aphids were widely distributed.

The subsequent population crash observed across all treatments at 9–10 WAS mirrors the classical population oscillations seen in specialized predator-prey systems (Omoregie and Ayefuwe, 2026). As the okra plants matured, declining phloem nutritional quality and increased intra-specific competition caused an aphid population crash, driving host availability below the critical threshold necessary to sustain parasitoid reproduction and recruitment (Van Emden and Harrington, 2017).

Table 2: Aphid natural enemy abundance as influenced by plant spacing and number of plants per stand across weeks after sowing

	Treatments						
WAS	**40×25×1**	**40×25×2**	**40×25 ×3**	**50×25×1**	**50×25×2**	**50×25×3**	**Sig.**
2	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.25 (0.84)	0.00 (0.71)	0.00 (0.71)^{b}	ns
3	0.25 (0.84)	0.50 (0.97)	0.00 (0.71)	0.25 (0.84)	0.50 (0.97)	0.00 (0.71)^{b}	ns
4	3.25 (1.77)	0.50 (0.97)	1.75 (1.22)	2.00 (1.41)	1.50 (1.35)	3.00 (1.69)^{a}	ns
5	1.50 (1.17)	3.75 (1.80)	2.00 (1.39)	1.25 (1.27)	0.75 (1.06)	0.75 (1.06)^{b}	ns
6	1.25 (1.26)	0.25 (0.84)	0.50 (0.97)	0.00 (0.71)	1.00 (1.13)	0.25 (0.84)^{b}	ns
7	1.25 (1.19)	1.25 (1.19)	0.25 (0.84)	4.00 (1.70)	0.50 (0.97)	0.00 (0.71)^{b}	ns
8	5.75 (1.91)	0.75 (1.06)	0.50 (0.93)	0.25 (0.84)	0.75 (1.06)	0.50 (0.97)^{b}	ns
9	0.25 (0.84)	0.75 (1.00)	2.00 (1.34)	0.00 (0.71)	0.25 (0.84)	0.25 (0.84)^{b}	ns
10	0.00 (0.71)	0.25 (0.84)	0.25 (0.84)	0.00 (0.71)	0.00 (0.71)	0.75 (1.10)^{b*}	*
Sig.	ns	ns	ns	ns	ns	*	

abMeans in the same column with different letter superscript are significantly different ($p < 0.05$), ns = Means in the same row and column are not significantly different at $p > 0.05$. Means in parenthesis are square root transformed

3.3 Trophic and Meteorological Interactions

Analysis of pooled aphid populations across meteorological weeks (Table 3) revealed that the absolute seasonal peak occurred during the 43rd meteorological week (corresponding to 8 WAS), reaching an aggregate of 1202 individuals/ five plants. This population peak coincided with a mean ambient temperature of 27.9 °C, a relative humidity of 82.4%, and a weekly rainfall total of 35.6 mm. Conversely, the pooled parasitoid population peaked earlier, during the 39th meteorological week (4 WAS**)**, averaging 14.50 individuals under a mean temperature of 26.5 °C, relative humidity of 87.2%, and substantially higher rainfall (82.1 mm).

Correlation analysis (Table 4) quantified the precise multi-trophic and abiotic relationships driving this system. Aphid abundance was positively and significantly correlated ($p < 0.05$) with braconid abundance ($r = 0.71$) and mean temperature (r = 0.86), but negatively correlated with relative humidity (r = –0.75) and total rainfall (r = –0.79). Braconid abundance demonstrated a significant positive correlation with host aphid density ($p < 0.05$), but showed no statistically significant direct correlation with any of the recorded meteorological parameters ($p > 0.05$). Among the abiotic variables, mean temperature exhibited a strong, highly significant ($p < 0.001$) negatively correlated with both relative humidity (r = –0.96) and total rainfall (r = –0.99), while relative humidity and total rainfall were strongly and positively correlated (r = 0.98***). The strong positive correlation between aphid and braconid abundance confirms the density-dependent tracking mechanism discussed previously. Braconid wasps actively forage and aggregate where host aphid patches are largest, meaning their populations in the field are primarily dictated by host biological availability rather than direct abiotic triggers (Van Emden and Harrington, 2017). This is further validated by the fact that wasp abundance maintained no significant correlation with weather metrics; their environmental response is indirectly mediated through the availability of their host (Kishinevsky *et al.*, 2017). Abiotically, temperature emerged as the primary driver of aphid population growth. As reported by Liu *et al.*, 2025: Temperature is the most important abiotic factor affecting development and reproduction of aphids. Ambient thermal conditions within the 15 ˚C - 28˚C range accelerate insect metabolic processes, shortening nymphal development periods and boosting adult fecundity (Ramalho *et al.,* 2015; Van Emden and Harrington, 2017). The peak population at 27.9 °C in this study represents an optimal thermal zone for *A. gossypii* reproduction in tropical environments. This strong positive relationship aligns with Jadhav *et al.* (2017), who documented high aphid infestations in summer okra under warm, bright regimes. It contrasts, however, with Sonawane *et al.* (2021), who reported a negative correlation with temperature during a cooler July–September rainy window, highlighting that the effect of temperature depends heavily on local seasonal timing.

Conversely, the strong negative correlations between aphid numbers and both rainfall and relative humidity highlight the suppressive impact of wet weather. Heavy tropical rainfall physically dislodges these soft-bodied insects from the host canopy, causing high mechanical mortality, while prolonged high humidity can promote epizootics of entomopathogenic fungi that collapse aphid colonies (Jadhav *et al.*, 2017; Van Emden and Harrington, 2017). While some studies in sub-humid zones show positive correlations between aphids and humidity due to extended host plant freshness (Abbas *et al.*, 2023), our study demonstrates that in the humid rainforest zone of Benin City, the interaction of high rainfall and extreme humidity acts as a major limiting factor for pests. The significant negative correlation between temperature and moisture metrics confirms that drier, warmer spells within the rainy season create the ideal window for aphid outbreaks. Consequently, periods of rising temperatures accompanied by declining rainfall accelerate aphid population growth, which subsequently triggers a density-dependent population expansion among indigenous braconid parasitoids.

Table 3: Abundance of aphids, wasp parasitoid and weather parameters across the meteorological weeks

Month	WAS	Met. Week	Aphid abundance	Parasitoid abundance	Relative Humidity (%)	Ave. Temp (˚C)	Rainfall (mm)
Sept	2	37	8.75	0.00	89.5	26.1	91.2
	3	38	91.50	1.50	88.0	26.3	85.5
	4	39	520.80	14.50	87.2	26.5	82.1
Oct	5	40	562.00	13.25	86.1	26.9	72.4
	6	41	770.80	4.50	85.5	27.2	61.8
	7	42	1032.00	10.25	84.0	27.5	50.3
	8	43	1202.00	12.50	82.4	27.9	35.6
Nov	9	44	894.50	6.50	80.1	28.2	18.2
	10	45	1006.00	4.50	76.5	28.4	12.5

Table 4: Correlation between aphid abundance, natural enemy abundance and weather parameters

	Aphid abundance	Parasitoid abundance	Mean Temperature	Relative Humidity	Total Rainfall
Aphid abundance	-				
Parasitoid abundance	0.71*	-			
Mean Temperature	0.86**	0.33ns	-		
Relative Humidity	-0.75*	-0.23ns	-0.96***	-	
Total Rainfall	-0.79*	-0.25ns	-0.99***	0.98***	-

***correlation is significant at $p < 0.001$, **correlation is significant at $p < 0.01$, ns = correlation not significant ($p > 0.05$)

4.0. Conclusion

This study evaluated the effects of plant spacing and stand density on aphid (*Aphis gossypii*) infestations and braconid wasp parasitoid dynamics in okra (*Abelmoschus esculentus*) cropping system in Benin City, Edo State. Specifically, it investigated how these planting configurations—previously optimized for yield—alter canopy architecture to influence pest and natural enemy abundance as a cultural integrated pest management (IPM) strategy. While closer spacing showed a slight numerical trend toward higher infestations, the lack of statistical significance indicates that farmers can adopt higher-density configurations, such as the optimal 40×25 cm yield spacing, without exacerbating pest outbreaks. Our findings demonstrate that macroclimate and crop phenology exert a more dominant influence on tri-trophic dynamics in this humid tropical rainforest zone than crop geometry. Aphid populations were primarily driven by crop ontogeny and weather, escalating during warm, dry, mid-to-late growth stages, while indigenous braconid wasps exhibited classic density-dependent tracking by aggregating as host availability increased.

5.0 Recommendation

Following these findings, smallholder management should focus less on crop arrangement and more on timing interventions with seasonal cycles. Farmers should adopt an integrated approach that aligns planting schedules with seasonal weather trends, intensifies field monitoring during late-season warm windows, and prioritizes native natural enemy conservation. Future research should expand the range of spacing treatments and increase plot dimensions to better capture distinct microclimatic effects on pest movement. Furthermore, these efforts should expand to multi-season trials across diverse agro-ecological zones to validate temporal trends against climate variability. Finally, incorporating in-canopy microclimatic sensors will provide deeper insights into how localized temperature and humidity gradients specifically influence aphid survival and parasitoid efficiency.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Gemini AI and co-pilot to source information, find related materials, and recast sentences. Thereafter, the authors reviewed and edited the content as needed and take full responsibility for the final version of this publication.

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