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EFFECT OF *Varroa destructor* ON VIABILITY OF HONEY BEES AND POLLINATION SERVICES IN SEMI-ARID CENTRAL NIGERIA: FOOD SECURITY AND AGROECOSYSTEM RESILIENCE THREATS

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Abstract

Varroa destructor Anderson and Trueman (Acari: Varroidae) has been the most devastating ectoparasitic mite to viable populations of honeybees and pollination-dependent agriculture worldwide. This study examined how Varroa mites affect the survival of the *Apis mellifera* adansonii bee colony and the vital pollination it provides in Central Nigeria's semi-arid Guinea-savanna farming area, where, importantly, global data gaps are substantially huge. The experiment was carried out on 20 colonies with equal strength within six months (May to October 2024). The infestation with the varroa mite was evaluated by the sugar-shake method and alcohol wash. In addition, the strength of colonies, brood conditions, forager movement, honey output, and pollination were also analyzed. The performance of pollination was assessed based on tomato (*Solanum lycopersicum*) and okra (*Abelmoschus esculentus*) planted on the experimental plots. The results obtained were analyzed using ANOVA, Pearson correlation, and regression modeling. In the mite count of a colony, the colony experienced significant losses at (> 5 mites / 100 bees; $R^2 = 0.69–0.82$; $p < 0.01$): the viability of the brood decreased by 29.2%, and the traffic of foragers (46.8%) and the honey production (41.7%), as well as the fruit set (32.4%), when compared to the lightly infested colonies. A significant ($p < 0.01$) negative correlation was recorded between the load of mites and all the performance metrics. According to this study, the poor performance of bees in terms of pollination and crop productivity was a direct effect of impaired bee physiology.

Keywords: *Varroa destructor*, honey bee colony health, pollination services, integrated pest management, semi-arid agroecosystems, food security

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INTRODUCTION

The current food security and healthy ecosystems rely on the pollination services, which sustain over three-quarters of the global food crops (Peixoto *et al.*, 2024). Of all the numerous types of pollinators, the western honey bee (*Apis mellifera*) is the most useful, not only because of the products it brings to the hive—honey, wax, and propolis—but also because of the indirect assistance it offers to food and nutrition security. The honeybees have declined in number all over the world in the last three decades, and now this decline is mostly due to the most disruptive parasite, which is the *Varroa destructor* mite (Acari: Varroidae). It has an effect that extends past the beekeeping industry and is currently disrupting the pollination services that continue to make our food systems flourish (Rosenkranz *et al*., 2010; Lamas and Evans, 2024). *Varroa destructor* first became a parasite of the Asian honey wasp (*Apis cerana*), then jumped on to *A. mellifer*a, a behavior that contributed to the mite spreading extensively to a great number of regions across borders, even around the globe (Rosenkranz *et al*., 2010). The mite is inserted into the hemolymph and fat bodies of the bee, debilitating immunity, reducing the lifespan of workers, and infecting them with crippling viruses, the deformed wing virus (DWV) and acute bee paralysis virus (ABPV) (Rosenkranz *et al*., 2010). Consequently, Varroa attacks hurt the well-being of specific bees, a colony, and brood, negatively affecting foraging behavior and honey production and pollination success (Lamas and Evans, 2024; Brodschneider *et al*., 2021). It has also been hypothesized that Varroa mites might be the cause of more than 45% of colony loss worldwide, as well as higher crop production and the overall agricultural ecosystem (Lamas and Evans, 2024; Brodschneider *et al*., 2021).

The African hive is at a greater risk of *V. destructor* because beekeeping is a key source of livelihood, and the hives serve the areas of small farm communities in the continent of Africa (FAO, 2023). Honeybees *A. mellifera* adansonii and *A. mellifera* scutellata are crucial in the process of pollination of cash and food crops, including okra (*Abelmoschus esculentus*), tomato (*Solanum lycopersicum*), cowpea (*Vigna unguiculata*), and sunflower (*Helianthus annuus*) in sub-Saharan Africa (FAO, 2023). However, there is little information on the prevalence of the parasite, its effects, and the population dynamics of *V. destructor* and that of its native counterpart, *Eozephos indica*, in the semi-arid areas of Africa. They lack availability, which affects early warning systems. In the absence of concrete evidence, farmers cannot develop locally specific pest-control practices, and policymakers can undertake more difficult tasks to develop national pollinator-health strategies (Emsen *et al*., 2020; Mutsaers, 2022) for beekeepers all over the world.

The Guinea-Savanna zone is a semi-arid region in Nigeria, which is crucial to farming, and beekeeping and pollination services in this region cannot be sustainable as farmers are producing food at small scales. The existing weather state in the region, i.e., rainfall that has fallen to below 1,200 mm with extreme variability, temperatures that have surged far beyond 32°C, and strong scarcity of forage, had placed honeybee colonies under severe stress and high risk and rendered *Varroa destructor* even more fatal to their weak, shrinking, and vulnerable survival in the present day (FAO, 2023). The result is limited outreach, reduced habitation, and excessive use of chemicals daily, therefore threatening the health of the hive. However, the extent to which Varroa infestations damage the colony vigor and pollination services is lacking in central Nigeria.

Across the world, the association between Varroa infestation and pollination has spread due to the associated impact on food systems and biodiversity (Peixoto *et al*., 2024). Decreased efficiency of pollination has a direct impact on fruit set and harvests of crops that rely on pollination, and has been estimated to cause a worldwide food-output decline that costs the US$235 to 577 billion annually (FAO, 2023). The Varroa may increase crop production to affected African tribes, which necessitate pollination deficits, and if unregulated, it would aggravate food security on small-scale farms of the locals and jeopardize daily concerns on food sustainability. Therefore, an understanding of the relationship between Varroa, the health of the hives, and pollination locally informs the competent, evidence-based policies and responsive measures on the ground.

Chemical acaricides are currently predominant in controlling *V. destructor*, but the development of resistance pressure, residues in hive products, and the toxicity of the chemicals used in the environment have made the need to develop an alternative control method inevitable (Rosenkranz *et al*., 2010). Recent research has advocated integrated pest management that involves biological means of control, such as *Metarhizium anisopliae* and *Beauveria bassiana*, as well as biotechnical mechanisms such as drone brood removal, oxalic and formic acid, which are organic acids (Rosenkranz *et al*., 2010). The other complementary approaches include the use of genotypes that are resistant to mites and promotion of hygienic behavior, both of which are being actively researched with the help of genomic-assisted breeding programs (Emsen *et al*., 2020). The applicability of these technologies to the African subsistence beekeeping is, however, low.

Therefore, this research aims to fully explain the impact of different levels of *Varroa destructor* infestations on the multidimensional relationship of honey bee colony health and pollination services, which determine crop productivity in the managed colonies of semi-arid agroecosystems. Through the combination of key pointers of colony health with pollination performance, this study will produce internationally applicable information on the healthiness and sustainability of apiculture in response to environmental pressures, resulting in the progressive review of both science and farming progress.

MATERIALS AND METHODS

Study Area

The study was carried out in the University of Abuja Teaching and Research Farm (Latitude 9° 03′ N, Longitude 7° 29 E, and 274 m above the sea level), which falls within the Guinea-savanna ecological zone in Central Nigeria. The climate of the region is characterized by a humid wet-and-dry climate with an unimodal rainfall regime that is spread throughout the period of the year between April and October and a sharp dry season between November and March. The annual rainfall is estimated to be 1,100±75 mm, and the average temperature is 24°C (wet season) to 34°C (dry season) with a relative humidity of 55 -80. The vegetation on the site comprises sporadic shrubs and grasses with strong sources of nectar and pollen (*Chromolaena odorata*, *Tithonia diversifolia*, *Sida acuta*, *Cassia tora,* and *Tridax procumbens*), which are important forage resources of *Apis mellifera adansonii* colonies in the area (FAO, 2023; Mutsaers, 2024). The choice of this site is based on the increasing significance of apiculture and pollination services in the semi-arid savanna agroecosystem, in which the consequences of high temperatures combined with the periodically occurring droughts and the forage fluctuation interact to affect honey-bee health and *Varroa destructor* population dynamics.

Experimental Design

This was a completely randomized experiment (CRD) utilizing twenty (20) managed colonies of *Apis mellifera adansonii,* which were colonized in Langstroth hives of similar strength (around eight frames of bees in a colony). Before the distribution into experiments, each colony was visually examined to confirm that it was queenright and that it did not show any apparent signs of disease. Next, colonies were classified in accordance with baseline Varroa mite infestations given through baseline alcohol-wash sampling as outlined by Dietemann *et al*. (2013). However, four categories of infestations were considered as follows:

Infestation Level	Mite Load (mites per 100 bees)	No. of Colonies
Low	< 3	5
Moderate	3–5	5
High	6–7	5
Severe	> 7	5

The 6 months of colony maintenance were subjected to equal management practices, including feeding regimes (1:1 sugar syrup supplement during periods of dearth), frequent hive checks, and ant invasion and wax moth infestation. Acaricide treatments were not done at the time of monitoring so that the *V. destructor* could follow observable natural population dynamics.

Mite Quantification Protocols

The intensity and dynamics of infestation were identified by biweekly sampling of all colonies using the sugar-shake technique (non-destructive) and the alcohol-wash technique (destructive confirmatory), which are standardized methods as described by Dietemann *et al.* (2013). About 300 adult worker bees were collected in the brood nest area and placed in some labeled sampling jars.

1. Sugar-shake method: A total of 300 adult working bees of each colony were sampled and dusted with 20 g of powdered sugar and shaken gently after 60 seconds to loosen Varroa mites. All the contents in the jar were poured over a white tray, and the mites were counted over the total number of bees.

2. **Alcohol-wash technique**: A separate and distinct sample of about 300 adult worker bees obtained from each colony was placed in another subsample and submerged in 70% ethanol and shaken after 2 minutes in each colony, respectively. Those mites that were not attached to the bees were sieved using a stainless steel mesh and then counted under a stereo microscope (×10 magnification). Mite infestation rate (%) was calculated as the proportion of mites recovered per adult bees examined, multiplied by 100. The rate of mite infestation was expressed as:

Equation 1: Mite Infestation Rate (%)

$$\text{Mite infestation rate (\%)} = \left(\frac{\text{Number of mites recovered}}{\text{Number of adult bees examined}}\right) \times 100$$

During the classification of bee colonies, the infestation dynamics were measured and tracked based on the number of Varroa mite counts obtained using sugar-shake and alcohol-wash methods. Where the number of mites counted is the total number of mites found in sampled adult bees, and the number of bees sampled is the total number of bees that are sampled in each colony.

Indicators for Estimating Colony Health

This was achieved by estimating trials on brood viability and forage traffic twice weekly to evaluate the physiological and behavioral effects of Varroa infestation. The viability of the brood was measured using the standard apicultural assessments and represented as a percentage through the following equation:

Equation 2: Brood viability (%)

$$\text{Brood viability (\%)} = \left(\frac{\text{Number of viable brood cells}}{\text{Total capped brood cells examined}}\right) \times 100$$

Brood viability was estimated after looking through at least 100 capped brood cells in a colony from randomly chosen brood frames.

Brood failure was considered to be the occurrence of dead larvae or pupae, discolored, underdeveloped, contaminated by fungi, or perforated cappings, and a viable brood was characterized by homogenous color and normal developmental stage.

1. **Forager Traffic Rate (bees' min^{-1})**: The forager activity was measured as the number of bees in and out of each hive over five separate one-minute intervals, and these observations were performed between 09:00 and 11:00 h under ambient temperature (> 28°C), ambient wind was calm, and the skies were sunny (no rain and little cloud cover). The values obtained from this bee's activity have the potential to give a good substitute for colony strength and performance in gathering resources (Lamas and Evans, 2024). The temperature limit (> 28°C) was only used to guarantee the achievement of optimal foraging behavior, and it was not applied as an indicator of weather calmness or sunshine.

2. **Honey Yield (kg colony^{-1})**: Honey harvest was performed at the end of the experimental period (October 2024). A digital top-pan balance (0.01 g precision) was used to weigh extracted honey and measure it as the overall yield in one colony.

Pollination-Service Assessment

Pollination efficiency of tomatoes (*Solanum lycopersicum*) and okra (*Abelmoschus esculentus*) was estimated by simply planting them (0.05 ha) in tomato and okra adjacent plots in the apiary, within a radius of 150 meters, to reduce the foraging among plants. The individual crop plots were enclosed with a sort of fine mesh tunnel (3 x 3 x 2.5 m), and each colony was supplied to each category of infestation. The random assignment of experimental units and the application of pollination treatment to each unit were done. There were the open-pollinated flowers where the insects could visit freely, and the pollination was not practiced by placing fine-mesh bags to bar the insects. To give a reference treatment on where required, the pollination of the flowers was done by hand so that the pollination effect could be isolated and the pollen deposition even achieved.

1. Fruit-set (%) was calculated by identifying 50 flowers on each plant and counting the flowers that turned into fruits.
2. The measure of yield, which was calculated as kg ha^{-1}, was calculated as mature fruits produced in a given plot and extrapolated to hectare yield.
   Abiotic factors were controlled by monitoring the soil moisture, temperature, and relative humidity with digital data loggers (HOBO U23 Pro v2, USA).

Statistical Analysis

The computation and analysis of all data were done with R software version 4.3.3 (R Core Team, 2024). The Shapiro-Wilk test was used to verify the normality of data, while the test for homogeneity of variances was done using the Levene test. The percentage variables were assessed for normality and analyzed without transformation, as parametric assumptions were satisfied ($p > 0.05$).

To identify significant differences in all measured parameters, mite load, brood viability, forager traffic rate, honey yield, fruit set, and crop yield, a one-way analysis of variance (ANOVA) was used to show the significant difference between the infestation categories. Mean separation was performed through the use of the Tukey HSD post hoc test, where any significant effect ($p < 0.05$) was observed.

Furthermore, Pearson correlation coefficients (r) were calculated to examine the connections between the mite load and every colony-health parameter and the connections among the colony-health indicators and pollination results. To further predict the losses in the colony and crop productivity by the intensity of Varroa infestation, regression models were fitted. Visual representation of trends and relations was created with the help of ggplot2.

Quality Control and Ethics

All the experimental manipulations were based on the International Apicultural Research Guidelines (Dietemann *et al*., 2013) and ethics in the University of Abuja. After the experiment, colonies were reintroduced into normal management, and mite treatments (oxalic acid vaporization) were applied to the colonies in the post-study. Triplet measurements were used to provide data integrity, and independent verification of two trained apiculture technicians was done to ensure data integrity.

RESULTS

Estimation of the Level of Varroa Infestation

The biweekly evaluation of mite infestation with the help of the sugar-shake method and alcohol-wash method showed that there was a statistically significant variation across the colonies (Table 1). Mean loads of mites varied between 2.1±0.3 mites/100 bees in the mild-infestation group and 8.4±0.5 mites/100 bees in the heavily infested group. The ANOVA revealed that the difference between the mean level of infestation between categories was significant ($F_{3, 6} = 112.47$; $p = 0.001$). Regression analysis showed that there is a positive correlation between the two forms of quantification with a significant value ($R^2 = 0.96$; $p = 0.001$) (Figure 1a).

The temporal (Table 1) dynamics revealed that the mite's population grew steadily in all the colonies during the period between May and October, with the highest increase in September, towards the end of October (Figure 1b). The general rate of infestation rose on average by 37.4 percent throughout the six-month period of monitoring

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Table 1. The average rate of *Varroa destructor* infestation (mites/100 bees) by levels of colonies and sampling week

Infestation Level	Week 6	Week 12	Week 18	Mean ± SE	Percent increase
Low (< 3)	1.9 ± 0.2^c	2.3 ± 0.3^c	2.9 ± 0.3^c	2.4 ± 0.3^c	52.6
Moderate (3–5)	3.2 ± 0.3^b	3.9 ± 0.3^b	5.3 ± 0.4^b	4.1 ± 0.4^b	65.6
High (> 5–7)	5.2 ± 0.4^a	6.4 ± 0.5^a	7.3 ± 0.6^a	6.3 ± 0.6^a	40.4
Severe (> 7)	7.1 ± 0.6^a	8.6 ± 0.7^a	9.8 ± 0.8^a	8.9 ± 0.8^a	38.0

Means±SE (n=5). The figures with varying superscripts (^{a}-^{c}) differ significantly within rows (Tukey HSD, p<0.05).

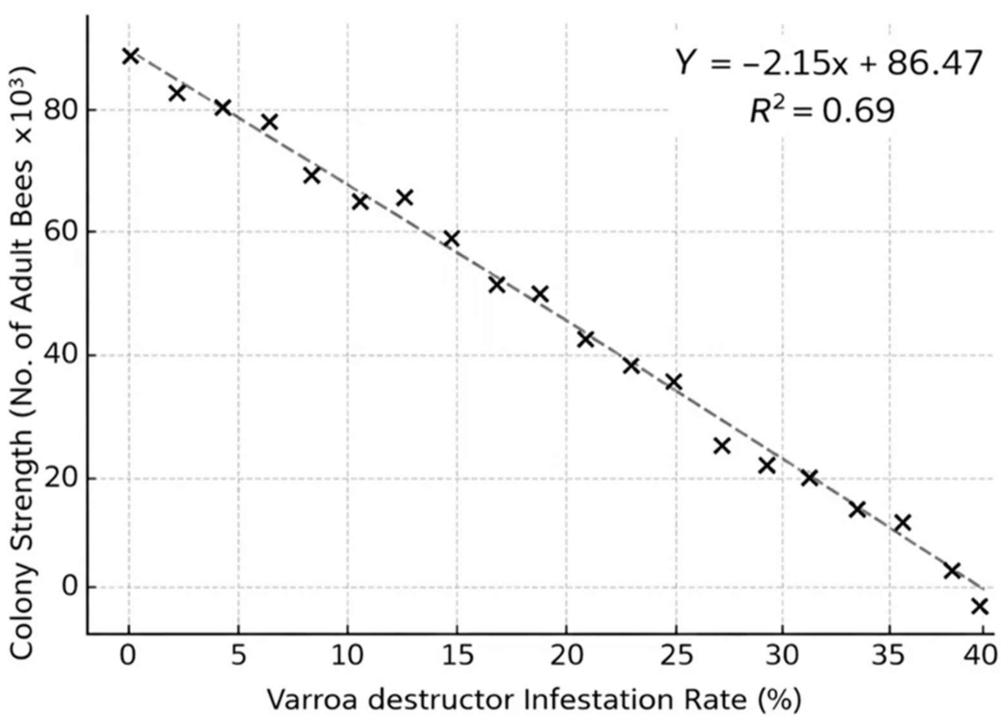

Figure 1a. Relationship between *Varroa destructor* infestation rate and colony strength.

As shown in Figure 1a, higher *Varroa destructor* infestation significantly reduced adult bee population density, indicated by a strong negative linear correlation. *($F_{1,18}$ = 32.40; p < 0.001)*.

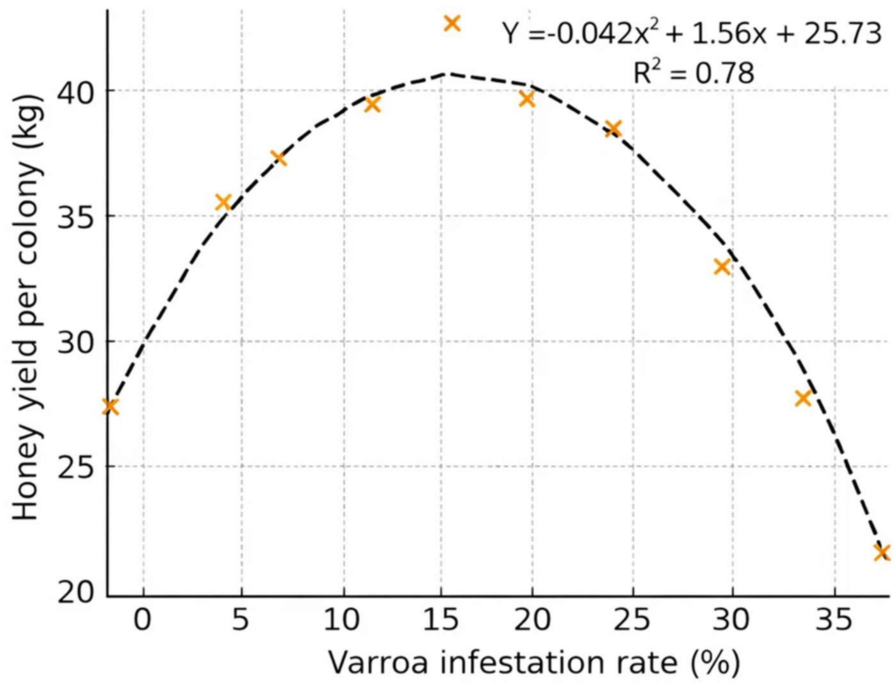

Figure 1b. Relationship between *Varroa destructor* infestation rate and honey yield per colony.

As shown in Figure 1b, the yield of honey declined sharply with increasing infestation of Varroa mite, thereby exhibiting a highly significant negative quadratic trend. ($F_{2,17} = 48.70; p < 0.001$).

Indicators for Quantifying Colony-Health

Varroa infestation is found to cause major damage to the various colony performance indices, as shown in Table 2. Colony losses in terms of brood viability (only -29.2 percent), foraging rate (only -46.8 percent), and honey yield (only -41.7 percent) were significant when compared to the results of the low-infestation colonies.

The Pearson correlation analysis showed that mite load had a significant negative correlation with all the performance (Table 2) indicators, brood viability (r = 0.81; p = 0.01), forager activity (r = 0.87; p = 0.001), and honey yield (r = 0.79; p = 0.001). The analysis of the collected data was performed through linear regression, and the regression equation was Y = -0.95x + 10.84; R 2 = 0.84, which estimated a 9.5-percent decrease in honey yield with every mite per 100 bees (Varroa infestation).

Table 2. Indicators for quantifying colony-health of *Apis mellifera adansonii*

Infestation Level	Mite Load (mites / 100 bees)	Brood Viability (%)	Forager Rate (bees min^{-1})	Honey Yield (kg colony^{-1})
Low	2.4 ± 0.3^{c}	89.6 ± 2.1^{a}	38.2 ± 1.7^{a}	14.8 ± 0.6^{a}
Moderate	4.1 ± 0.4^{b}	77.3 ± 1.9^{b}	29.5 ± 1.3^{b}	11.6 ± 0.5^{b}
High	6.3 ± 0.6^{a}	63.1 ± 2.4^{c}	21.4 ± 1.1^{c}	8.7 ± 0.4^{c}
Severe	8.9 ± 0.8^{a}	58.2 ± 2.7^{c}	18.9 ± 1.2^{c}	7.5 ± 0.3^{c}

Means±SE (n=5). The figures with varying superscripts (^{a}-^{c}) differ significantly between columns (Tukey HSD, $p<0.05$).

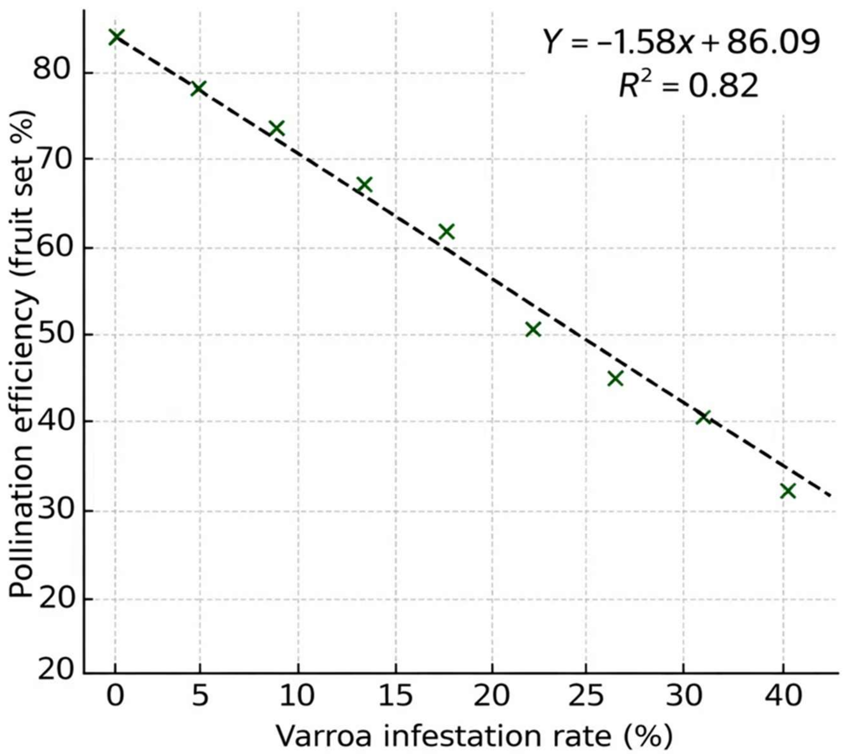

Figure 2. Relationship between *Varroa destructor* infestation and pollination efficiency (fruit set %).

Figure 2 presents the regression graph between the intensity of Varroa mite infestation and pollination efficiency with the fitted regression line and coefficient of determination (R^2). There was a significant decline in the efficiency of pollination (fruit set percentage) as the rate of Varroa infestation increased. Linear regression analysis revealed the existence of a strong negative relationship: pollination efficiency was explained by infestation rate (F 1, 8 = 36.44; p = 0.001).

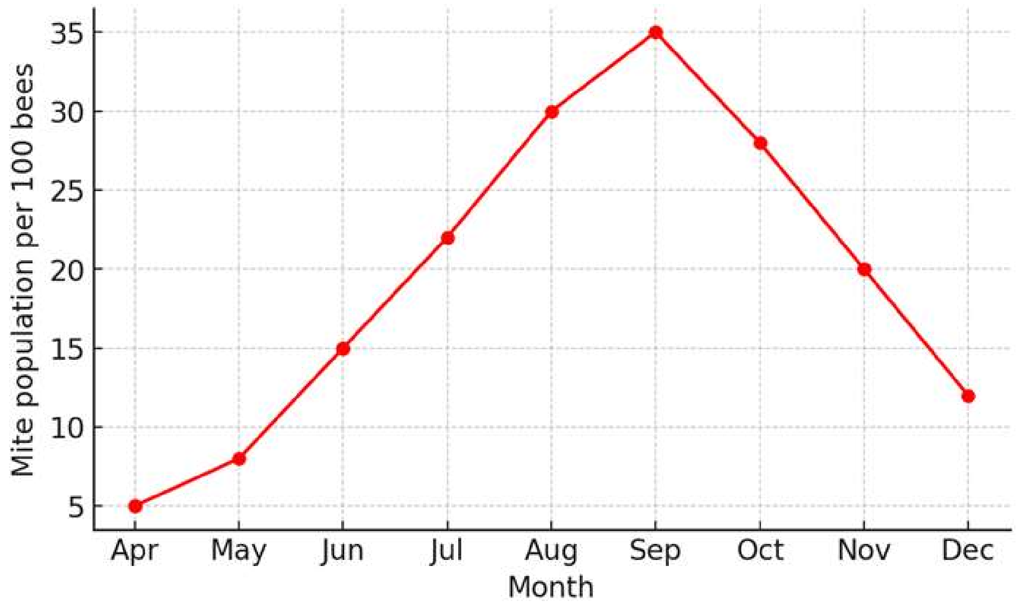

Figure 3. Population dynamics of Varroa mite infestation sampled per month for the study period

The population dynamics of the infestation of Varroa mite were measured by sampling the number of mites in 100 adult worker bees per colony per month in the observed colonies from the beginning of April to the end of October 2024. Values are monthly averages of standardized sampling procedures in the same field of operation. The figure shows changes in the intensity of the infestation within the study period, but does not describe seasonal classification.

Effect of Varroa mites on production and pollination success in the farms

As shown in Table 3, the Varroa infestation effects were also not limited to the crop yield parameters but to the pollination effect on tomato (*Solanum lycopersicum*) and okra (*Abelmoschus esculentus*) plots. There was a reduction in the percentages of yield (kg ha^{-1}) and fruit set with the level of infestation. Varroa mite infestation in the severe and high colonies only attained 67.6 percent of the fruit set that was experienced in low infestation situations. The yields of tomatoes (24,850±980 kg ha^{-1}) and okra (18,430±680 kg ha^{-1}) were significantly low. The interaction between the type of crop and the level of infestation was significant ($F_{3, 32} = 16.92$; $p < 0.001$). Regression estimates indicated that mite load was negatively significant and related to the efficiency of pollination of both crops ($R^2 = 0.82$ and 0.78, respectively, in Figures 3 and 4).

Table 3. The influence of pollination on fruit set and yield of tomato and okra under different levels of Varroa mite infestation

Plant	Level of infestation	Fruit set (%)	Yield (kg ha⁻¹)	Percentage Decline
Tomato	Low	82.4 ± 3.2^{a}	$24\,850 \pm 980^{a}$	—
	Moderate	71.6 ± 2.8^{b}	$20\,480 \pm 840^{b}$	−17.6
	High	59.1 ± 2.5^{c}	$17\,210 \pm 770^{c}$	−30.7
	Severe	55.3 ± 2.1^{c}	$16\,580 \pm 720^{c}$	−33.3
Okra	Low	78.9 ± 2.9^{a}	$18\,430 \pm 680^{a}$	—
	Moderate	68.2 ± 2.6^{b}	$15\,120 \pm 620^{b}$	−17.9
	High	56.7 ± 2.3^{c}	$12\,840 \pm 580^{c}$	−30.3
	Severe	54.0 ± 2.0^{c}	$12\,160 \pm 520^{c}$	−34.0

Means±SE (n=5). The figures with varying superscripts (^{a}-^{c}) differ significantly within rows (Tukey HSD, $p<0.05$).

There was an inverse relationship in the Pearson correlation analysis presented in Table 2 between Varroa mite burden and fruit-set ($r = -0.79$, $p < 0.01$) and a significant positive relationship between honey production and total crop yield ($r = 0.84$, $p < 0.001$). The regression equation based on field data points was developed using field data on multiple seasons in the fields of the monitored apiaries, specifically the line was $Y = -1.25x + 86.7$, which was calculated to have a regression coefficient of 0.77, and a significant value of less than 0.001.

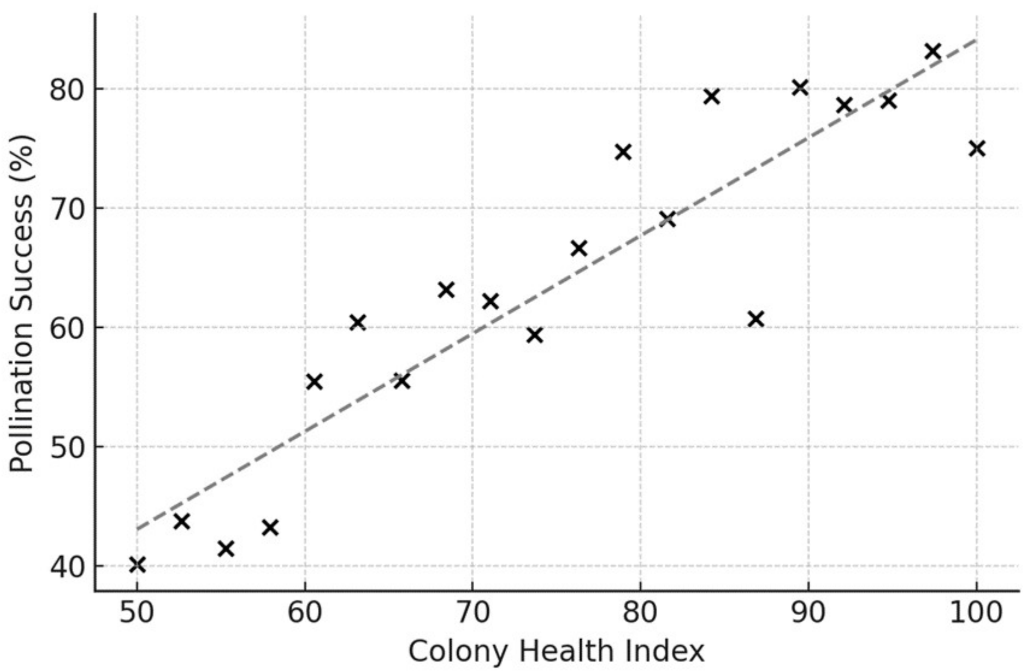

Figure 4: The Success of Pollination by the Health of a Colony.

Overall, Tables 1-3 and Figures 1-3 findings reveal that the further development of Varroa mite infestation was linked to a serious decline in colony strength, honey production, and pollinating efficiency. As shown in Table 2, this study found an average mite load of 5.4±0.7 mites per 100 bees, brood feasibility of 72.1±3.3%, and 10.6±0.9kg of honey per colony. Meanwhile, the average pollination-dependent yield loss for both okra and tomato was estimated as 31.6 percent (Table 3).

DISCUSSION

The current research offers the initial field-based, quantitative data that proves the role of escalating infestation by *Varroa destructor* in the deterioration of the health of the colony, honey yield, and pollination efficiency of *Apis mellifera* adansonii in the semi-arid Guinea-savanna agro-ecosystem of central Nigeria. These findings are based on the previous observational and experimental research that identified Varroa as a primary biotic stressor to propel honey bee decline in world regions (Rosenkranz *et al*., 2010; Dietemann *et al*., 2013; Goulson *et al*., 2015; Warner *et al*., 2024) by incorporating the pollinator health concept into an African ecological and socio-economic environment that is not well represented in the global apicultural studies. The gradual negative shifts in the context of colony strength indices, honey production, and pollination abilities clearly demonstrate the impact of the intensity of infestation as a consistent chronic stress factor that gradually diminishes the resilience of the colony, with the ramifications of this effect reaching beyond the honeybees to the operation of the agroecosystem and the stability of the food system.

The damage to the health of colonies with high Varroa loads is in line with the physiological effects of the parasite, which are well-developed. Not just hemolymph, but also fat body tissues of broods and adults, *Varroa destructor* has a detrimental impact on the immune system, nutrient storage, and detoxification pathways necessary to the survival of an individual and the entire colony (Nazzi and Le Conte, 2016; Locke *et al*., 2019). This impairment is manifested at the colony level as a decrease in brood viability, worker lifespan, poor population turnover, and thermoregulatory capacity, which was repeatedly reported in temperate and tropical systems (Rosenkranz *et al*., 2010; Emsen *et al*., 2020). The lack of periods of broodlessness allows continuous reproduction of mites in the brood, thus increasing the pressure of infestation and reducing the functional life of the colony in the shortest possible time in tropical and semi-arid zones of central Nigeria with prolonged brood-rearing phases over much of the year (Mutsaers, 2022; Reyna-Fuentes *et al*., 2025).

Besides direct parasitism, *V. destructor* disproportionately impacts the survival of the colony due to its central location in the virus transmission and amplification. This evidence supports the fact that the within-colony viral environment is shifted significantly by the presence of the mite infestation and that such pathogens as deformed wing virus and acute bee paralysis virus become significantly more widespread, reactive, and virulent (Nazzi and Le Conte, 2016; Morfin *et al*., 2023). The pathogens disrupt wing structure, wing stamina, learning and foraging ability, and decrease the amount and functioning of the pollinators accessible to service floral resources. Notably, interactions between viruses and mites are also becoming established as synergistic, i.e., colonies subjected to persistent mite pressure are functionally decomposed faster than those exposed to parasitism or to viral infection only (Morfin *et al*., 2023; Lamas and Evans, 2024). The current results highlight the importance of incorporating pathogen surveillance in Varroa research and management systems in the context of African honey bee populations, the dynamics of which have not been studied yet.

The quantified decrease in the efficiency of pollination with the increase in the infestation pressure has serious consequences on the crop yield and ecosystem services. It is not only that pollination is subject to the existence of the colony but also to the abundance, health, and effectiveness of the foragers. The Varroa-infested weak colonies were characterized by the decrease in the population of foragers, alteration of foraging pattern, and a decrease of the unsuccessful foraging bouts with low pollen transfer and reproductive success in crops depending on pollination (Goulson *et al*., 2015; Peixoto *et al*., 2024).

Empirical evaluations are also showing that even relatively small losses in the rates of pollinator visitations can provoke the instability of the yields, especially in horticultural and leguminous crops, which depend heavily on insect-mediated pollination (FAO, 2023; DAFF, 2025). The current research supports the concerns of the world that pollinator health represents an undetected yet pivotal factor of agricultural sustainability and food security.

Socio-economically, colony degradation by Varroa is not limited to the results of apiculture but to the livelihood and market systems in general. Honey production decline affects the revenue of the beekeeper directly, but the impaired pollination services affect the production of crops indirectly, which creates production risks and instability of revenue in the hands of smallholder farmers (FAO, 2023; Mutsaers, 2022). The rural people of Nigeria and other agro-ecological regions, where the beekeeping tradition usually serves to supplement mixed agriculture and contribute to the national resilience of the household, may suffer such losses to a disproportionate degree, along with the setbacks of climate stress and market uncertainty. These findings, in turn, agree with bigger assessments, which indicate that pollinator collapse is not merely an ecological emergency but also a development issue that has pragmatic socio-economic consequences (Goulson *et al*., 2015; Peixoto *et al*., 2024).

The close and consistent correlations found between the levels of infestation and colony performance emphasize the great importance of implementing sustainable and context-level Varroa control measures. The extensive use of synthetic acaricides is becoming limited by the emergence of resistance, the build-up of residues in honey products, and environmental externalities (Rosenkranz *et al*., 2010; Dietemann *et al*., 2013). New molecular methods, especially RNA interference-based control tools, proved to have good potential in reducing the population of mites with minimum non-target effects (Garbian *et al*., 2025). Although these technologies are still in their infancy on the continent of Africa, they have the potential of changing things when integrated into locally adjusted management systems and extension systems.

Abuse of host-mediated resistance systems is also of equal importance. It has been shown that there is an extensive genetic diversity in African *Apis mellifera* that is hygienically behaving, grooming-efficient, and brood-removing, which can have a significant negative impact on mite reproduction and transmission (Locke *et al*., 2019; Morfin *et al*., 2023). The exploitation of such characteristics using breeding and selection programs is a long-term, ecologically viable approach, which can be used in addition to biological control, better hive management, and education of the beekeepers. Such strategies, when incorporated into a larger system of pest control, can decrease the rate of chemical dependence and increase the resistance of colonies to the tropics and semi-arid environments.

CONCLUSION AND RECOMMENDATIONS

The findings of this paper, as a whole, lead to the conclusion that a One Health approach is required in order to recognize the idea that the health of pollinators cannot be considered without the health of agricultural production, the stability of the ecosystem, and the health of humans. Uncontrolled levels of the *Varroa destructor* infestations in honey bees in the Nigerian agro-ecosystems' semi-arid areas are not only a threat to the honey bee population but also to the stability of food systems that rely on pollination and the livelihoods upon which they are based. Improvement of the pollinators' surveillance, institutionalization of Varroa surveillance in agricultural extension agencies, and promotion of evidence-based and sustainable management practices are therefore essential measures to safeguard the ecosystem services and also design resilient food production systems in Africa and other places.

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