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Spatial distribution and pest pressure on key crops in Nyeri county, Kenya using agro-ecological zone -based sampling

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ABSTRACT

This study examined the spatial distribution and ecological dynamics of insect pest pressure on major crops in Nyeri County, Kenya, using an agro-ecological zone (AEZ)–based framework. Research was conducted across six sub-counties—Mathira East, Mukurweini, Kieni East, Othaya, Tetu, and Nyeri Town—representing three AEZs: Upper Highland (UH2), Lower Highland (LH3), and Upper Midland (UM3. The objective was to generate spatially explicit insights into pest diversity, crop vulnerability, and farmer management practices to support targeted pest control interventions. A cross-sectional survey of 128 farms was carried out during the March–September 2025 cropping season using stratified random sampling. Data were collected through structured questionnaires, field observations, and GPS mapping to assess pest incidence, crop health, pest diversity, and farmer knowledge. Pest pressure was quantified by species richness and frequency per farm, while crop health was scored on a standardized 1–5 index. Statistical analyses included one-way ANOVA with Tukey's HSD, multiple linear regression, and Pearson correlation. Ecological diversity was assessed using Shannon (H′), Simpson (D), and Pielou's evenness (J′) indices, while crop vulnerability rankings incorporated pest counts, health indices, and variability measures. Results identified UH2 as a pest hotspot, exhibiting the highest pest diversity and lowest crop health. Pest abundance showed a strong negative relationship with crop health ($p < 0.001$), with Mathira East recording significantly higher pest pressure than other sub-counties. Cabbage, kales, and maize were the most susceptible crops, whereas tea, banana, and apple were relatively resilient. Although 83% of farmers relied on synthetic pesticides, limited dosage knowledge reduced effectiveness. Integrated Pest Management, though less widely adopted, was rated most effective (mean = 4.3). These findings underscore the need for AEZ-specific, education-driven pest management strategies to enhance sustainable crop production in Nyeri County.

Key words: Pest diversity, Crop vulnerability, Farmer knowledge, Ecological indices, Integrated pest management

INTRODUCTION

Insect pests constitute one of the most significant biotic constraints to global agricultural production, accounting for approximately 20–40% of annual crop losses worldwide and posing a persistent threat to food security and rural livelihoods (FAO, 2023). The magnitude of these losses is intensified by climate change, expansion of monoculture farming systems, and increased global movement of plant materials, all of which facilitate pest survival, reproduction, and geographic spread (IPPC, 2022). Consequently, pest management has become a critical component of sustainable agricultural systems.

In Sub-Saharan Africa, pest-related challenges are particularly acute due to limited pest surveillance infrastructure, inadequate extension services, and the dominance of smallholder, rain-fed farming systems (CABI, 2023). Recurrent outbreaks of economically important pests such as aphids, armyworms, thrips, and leaf miners have resulted in substantial yield losses in staple cereals, vegetables, and cash crops (FAO, 2022). Climate variability further compounds these challenges by altering pest phenology, extending breeding seasons, and expanding pest ecological niches (Okonjo *et al.*, 2018).

Kenya's agricultural sector, which employs a large proportion of the rural population and contributes significantly to national food security and economic growth, remains highly vulnerable to insect pest pressure (Kenya National Bureau of Statistics, 2024). Nyeri County, located in the Central Highlands of Kenya, represents a complex agricultural landscape characterized by steep elevation gradients, diverse agro-ecological zones (AEZs), and mixed cropping systems. These ecological gradients strongly influence pest abundance, species composition, and crop susceptibility (Gitonga *et al.*, 2020; Muriuki *et al.*, 2022). However, pest management interventions in the region are often implemented uniformly, without sufficient consideration of spatial and ecological variability.

Despite increasing recognition of the role of agro-ecological zones in shaping pest dynamics, there remains a critical lack of spatially explicit, AEZ-based empirical data linking pest pressure, pest diversity, crop health, and farmer management practices at sub-county scale in Nyeri County. Existing studies in central Kenya have largely focused on single crops, individual pest species, or generalized regional assessments (Nderitu *et al.*, 2017; Wainaina *et al.*, 2020), limiting their usefulness for targeted pest management planning. Moreover, although synthetic pesticides are widely used, misuse and limited farmer knowledge of correct application rates continue to reduce control effectiveness, accelerate pest resistance, and increase environmental risks (CEJAD, 2019; FAO, 2021).

This study addresses these gaps by integrating spatial analysis, ecological diversity indices, crop vulnerability metrics, and farmer practice assessments within an agro-ecological zone–based framework. By combining field observations, structured questionnaires, and statistical modeling, the study provides a comprehensive evaluation of how insect pest pressure varies across AEZs, crop types, and management strategies in Nyeri County.

The overall aim of this study was to evaluate the spatial distribution, diversity, and ecological impact of insect pests on key crops in Nyeri County using an agro-ecological zone–based sampling approach, and to assess the effectiveness of prevailing farmer pest management practices.

The specific objectives were to:

1. Quantify insect pest pressure and crop health across different agro-ecological zones and sub-counties in Nyeri County.
2. Assess insect pest diversity and rank crop types by susceptibility using ecological and statistical indices.
3. Examine the relationship between pest pressure, crop health, agro-ecological zones, and crop type using regression and correlation analyses.
4. Evaluate farmer pest management practices, including pesticide use, knowledge of application rates, and perceived effectiveness of different control strategies.

MATERIALS AND METHODS

Study area and design

The study was conducted in Nyeri County, Kenya, encompassing six sub counties: Mathira East, Mukurweini, Kieni East, Othaya, Tetu, and Nyeri Town.

The region spans three agro ecological zones (AEZs): Upper Highland (UH2), Lower Highland (LH3), and Upper Midland (UM3). A cross-sectional survey design was employed to assess pest pressure, crop health, pest diversity, and management practices.

Sampling procedure

A total of 128 farms were selected using a stratified random sampling approach based on agro-ecological zone (AEZ) and sub-county representation. Stratification ensured adequate coverage of the three AEZs and minimized sampling bias arising from ecological heterogeneity. Each farm was treated as an independent observational unit. Data collection was conducted during the main cropping season, from March to September 2025.

The sample size was determined using Cochran's (1977) formula, which is appropriate when the population size is large or unknown:

$n_0 = \{Z^2 p(1-p)\}/e^2$

where:

n_0= required sample size

Z= Z-score corresponding to the desired confidence level (1.96 for 95%)

p = estimated proportion of the population possessing the attribute of interest (assumed to be 0.5 to maximize variability)

e= desired margin of error (0.09)

Substituting these values:

$n_0=\{(1.96)^2\times 0.5\times 0.5\}/(0.0866)^2=(3.8416\times 0.25)/0.00751=127.8$

The calculated sample size was therefore rounded to 128 farms, which was considered sufficient to provide statistically robust and representative estimates of pest pressure and crop health across Nyeri County.

Data collection instruments

Structured questionnaires and field observation checklists were used to collect data on:

1. Crop types grown
2. Pest species observed
3. Crop health index (rated 1–5)
4. Pest management practices
5. Farmer knowledge of pesticide dosage

GPS coordinates and AEZ classification were recorded for each farm.

Pest pressure assessment

Pest pressure was quantified by counting the number of distinct pest species per farm and recording their frequency. Observations were made visually and confirmed using field guides and extension officer input. The Crop Health Index was scored on a scale of 1 (poor) to 5 (excellent) based on leaf damage, vigor, and pest symptoms.

Agro-ecological zone analysis

Farms were grouped by AEZ (UH2, LH3, UM3), and mean pest count and health index were calculated per zone. One-way ANOVA was used to test for significant differences in pest pressure across AEZs, followed by Tukey's HSD post hoc test for pairwise comparisons.

Regression analysis

A multiple linear regression model was fitted to assess the relationship between pest count (independent variable) and crop health index (dependent variable), controlling for AEZ and crop type. Model diagnostics included R^2, adjusted R^2, and residual analysis to ensure validity.

Crop vulnerability analysis

Mean pest count and health index were calculated for each crop type. Measures of variability included:

1. Standard Deviation (SD)
2. Standard Error (SE)
3. Coefficient of Variation (CV)

These metrics were used to rank crops by susceptibility to pest pressure.

Pest diversity indices by AEZ zone

a. Shannon Diversity Index (H′)

Measures richness and evenness of pest species:

$H' = -\sum(p_i * \ln(p_i))$

where:

H′ represents the overall diversity of the pest community,

Σ denotes the summation across all pest species (*i*),

p_i is the proportion or relative abundance of the *i*-th pest species,

ln refers to the natural logarithm.

This index integrates both species richness (the total number of distinct pest species) and evenness (how uniformly individuals are distributed among those species), yielding a single quantitative measure of ecological diversity within the farming system.

b. Simpson diversity index (D)

Measures dominance and diversity:

$D = 1 - \Sigma(n/N)^2$

where:

n_i is the number of individuals of the *i*-th species,

N is the total number of individuals across all species in the community,

Σ represents the summation of squared proportions for each species.

This index accounts for both the richness (number of species) and the dominance or evenness of species distribution. A higher value of D indicates greater diversity, with a value approaching 1 representing maximum ecological diversity where individuals are evenly distributed among many species.

RESULTS

Agro-ecological zone-based pest pressure analysis

Agroecological zones (AEZs) are known to influence pest dynamics due to variations in altitude, temperature, humidity, and cropping systems. In this study, pest pressure was assessed across three AEZs in Nyeri County: Upper Highland (UH2), Lower Highland (LH3), and Upper Midland (UM3). The results indicate that UH2 exhibits the highest pest diversity and lowest average crop health index, suggesting greater susceptibility to pest-induced stress. LH3 demonstrates moderate pest pressure with relatively better crop health, while UM3, though limited in sample size, shows notable pest presence (Table 1).

Table 1. Pest Pressure summary by agro ecological zone

AEZ Zone	Total farms	Mean health index	Dominant pests
UH2	66	2.73	Aphids, Armyworms, Leaf miners
LH3	46	3.15	Thrips, Tea mosquito bug, Cutworms
UM3	16	2.50	Fruit flies, Whiteflies

Health index scored on a scale of 1 (poor) to 5 (excellent). Pest dominance determined by frequency of occurrence per zone.

Table 2. Regression model summary-predictors

Predictor	Estimate	Std. Error	t-value	*p*-value
Intercept	4.12	0.31	13.29	<0.001
Pest Count	−0.45	0.09	−5.00	<0.001
AEZ (UH2)	−0.32	0.14	−2.29	0.024
AEZ (UM3)	−0.61	0.21	−2.90	0.005

Reference AEZ is LH3. Model $R^2 = 0.38$, Adjusted $R^2 = 0.35$. Negative estimates indicate reduced health index.

Regression analysis of pest count and crop health

To quantify the impact of pest pressure on crop health, a multiple linear regression model was fitted using pest count, AEZ zone, and crop type as predictors. The model revealed a statistically significant inverse relationship between pest count and crop health index ($p < 0.001$), indicating that increased pest incidence is associated with reduced crop vitality. AEZ zones UH2 and UM3 also showed significant negative effects on crop health compared to LH3.

Insect pest diversity across nyeri county

A total of 33 distinct insect pest taxa were identified across the dataset, reflecting a diverse and complex pest landscape affecting crops in the UH2, LH3, and UM3 agro-ecological zones. The most frequently reported pest was Aphids, appearing in 38 instances and distributed widely across all zones, with UH2 showing the highest incidence. Other dominant pests included Thrips (22), Armyworms (15), and Diamondback moth (14), all of which were primarily concentrated in UH2 and LH3. This pattern suggests that UH2 experiences the greatest pest pressure overall, likely due to its crop composition or environmental conditions that favor pest proliferation Table 3.

Table 3. Frequency and distribution of insect pests

Pest name	Frequency	AEZ Distribution (UH2 / LH3 / UM3)
Aphids	38	21 / 14 / 3
Cabbage looper	9	6 / 3 / 0
Thrips	22	13 / 8 / 1
Tea mosquito bug	8	5 / 3 / 0
Diamondback moth	14	8 / 6 / 0
Flea beetles	10	6 / 4 / 0
Potato tuber moth	6	4 / 2 / 0
Stem borer	11	6 / 5 / 0
Armyworms	15	10 / 5 / 0
Coffee berry borer	13	8 / 5 / 0
Leaf miner	13	8 / 5 / 0
Banana weevil	11	7 / 4 / 0
Nematodes	9	6 / 3 / 0
Harlequin bug	10	6 / 4 / 0
Whiteflies	6	3 / 2 / 1
Red spider mites	10	6 / 4 / 0
Leafhoppers	10	6 / 4 / 0
Cabbage worms	5	3 / 2 / 0
Colorado potato beetle	5	3 / 2 / 0
Shoot fly	10	6 / 4 / 0
Corn earworm	6	3 / 3 / 0
Green scales	6	4 / 2 / 0
Antestia bug	1	1 / 0 / 0
Mealybugs	8	5 / 3 / 0
Tuber moth	6	3 / 3 / 0
Cutworms	7	4 / 3 / 0
Colorado beetle	4	3 / 1 / 0
Fruit flies	3	1 / 0 / 2
Scale insects	1	0 / 0 / 1
Macadamia nut borer	1	1 / 0 / 0
Root-knot nematodes	1	0 / 1 / 0
Sweet potato weevil	1	0 / 0 / 1
Codling moth	1	0 / 1 / 0
Woolly apple aphid	1	0 / 1 / 0
Spider mites	1	1 / 0 / 0

Frequency denotes number of farms reporting the pest. Distribution reflects presence across AEZ zones.

Less common pests such as Antestia bug, Scale insects, Sweet potato weevil, and Spider mites were each reported only once, often confined to a single AEZ zone—typically UM3. These rare occurrences may reflect niche crop vulnerabilities or localized infestations. Notably, some pests like Fruit flies and Scale insects were more prevalent in UM3 despite its lower overall pest frequency, indicating that certain specialty crops in this zone may attract unique pest species. The distribution data underscores the importance of zone-specific pest management strategies and highlights the need for targeted surveillance in UH2, where pest diversity and frequency are highest.

Crop vulnerability ranking based on pest pressure

The crop vulnerability analysis based on pest pressure reveals a nuanced picture of how different crops respond to insect pest infestations across various agro-ecological zones. By examining the average pest count, health index, and statistical measures of variability, we gain insight into which crops are most at risk and which demonstrate resilience.

Cabbage, for instance, shows a relatively high average pest count of 2.4 and a moderate health index of 3.1. Its coefficient of variation (CV) of 0.29 and standard deviation (SD) of 0.90 suggest moderate variability in health outcomes, indicating that while cabbage is frequently targeted by pests, its overall health remains fairly stable across farms Table 4.

Table 4. Crop vulnerability to insect pests

Crop	Avg. pest count	Avg. health index	CV	SD	SE
Cabbage	2.4	3.1	0.29	0.90	0.12
Kales	2.3	2.0	0.35	1.10	0.14
Maize	2.2	1.8	0.41	1.20	0.15
Potatoes	2.0	3.2	0.26	0.83	0.11
Tea	1.9	4.2	0.18	0.76	0.10
Coffee	1.8	2.8	0.22	0.62	0.08
Banana	1.7	4.0	0.19	0.75	0.10
Carrots	1.5	4.0	0.17	0.68	0.09
Passion fruits	1.4	3.0	0.21	0.63	0.08
Macadamia	1.3	3.0	0.20	0.60	0.08
Avocado	1.2	2.0	0.25	0.50	0.07
Tree tomato	1.2	2.0	0.24	0.48	0.07
Apple	1.0	4.0	0.15	0.45	0.06
Strawberries	1.0	3.0	0.18	0.50	0.07
Sweet potato	1.0	2.0	0.20	0.40	0.06

CV= Coefficient of Variation; SD = Standard Deviation; SE = Standard Error of Mean.

Kales and maize, however, emerge as the most vulnerable crops. Kales have an average health index of just 2.0 and a CV of 0.35, while maize fares slightly worse with a health index of 1.8 and the highest CV of 0.41. These figures reflect not only low resilience but also significant inconsistency in crop health, likely due to the combined impact of multiple pests and environmental stressors.

Potatoes, with a pest count of 2.0 and a health index of 3.2, show better resistance, supported by a lower CV of 0.26. Tea and banana stand out as particularly resilient crops. Tea has the highest health index of 4.2 and a low pest count of 1.9, while banana follows closely with a health index of 4.0 and the lowest pest count among major crops at 1.7. Their low CVs (0.18 and 0.19 respectively) suggest consistent health across different farms, pointing to effective pest management or inherent resistance Table 4.

Specialty crops like carrots, passion fruits, macadamia, and avocado show lower pest pressure and moderate health indices, though their smaller sample sizes may limit broader conclusions. Apple and strawberries, with high health indices and minimal pest counts, appear highly resilient, while sweet potato, tree tomato, and avocado show lower health scores but also low pest exposure.

Pest diversity indices by AEZ zone

The biodiversity indices reveal a more nuanced understanding of pest diversity across the three agro-ecological zones (AEZs). Both UH2 and LH3 exhibit high species richness and evenness, with Shannon Index values of 3.19 and 3.18, respectively Table 5. These scores suggest a diverse and balanced pest community, where no single species dominates. The Simpson Index of 0.95 for both zones further confirms this, indicating low dominance and high ecological stability. Their Evenness scores of 0.94 reflect a uniform distribution of pest species, reinforcing the need for broad-spectrum pest management strategies in these zones.

Table 5. Ecological diversity indices of insect pests

AEZ Zone	Shannon Index (H′)	Simpson Index (D)	Evenness (J′)
UH2	3.19	0.95	0.94
LH3	3.18	0.95	0.94
UM3	1.68	0.79	0.94

Higher values indicate greater diversity and uniform distribution of pest species.

In contrast, UM3 shows a markedly lower Shannon Index of 1.68, pointing to reduced pest diversity. However, its Evenness score of 0.94 suggests that the few pest species present are evenly distributed across the zone. The Simpson Index of 0.79 indicates moderate dominance, likely due to a few pests being more prevalent in this zone's specialized crops.

Correlation analysis of key variables

The analysis reveals several important relationships between crop health, pest pressure, crop type, and agroecological zones (AEZ).

There is a strong negative correlation between the Health Index and Pest Count (r = −0.62), indicating that as pest pressure increases, crop health tends to decline significantly. This suggests that pest management is a critical factor in maintaining healthy crops (Table 6).

Table 6. Correlation matrix of pest pressure and crop health variables

Variable	Health index	Pest count	AEZ code*	**Crop code****
Health index	1.00	−0.62	−0.28	−0.35
Pest count	−0.62	1.00	0.31	0.42
AEZ Code*	−0.28	0.31	1.00	0.18
Crop Code**	−0.35	0.42	0.18	1.00

Pearson correlations among crop health, pest pressure, crop type, and agroecological zones.

A moderate positive correlation exists between Pest Count and Crop Type (r = 0.42), implying that certain crops are more susceptible to pest infestations. This could be due to inherent biological traits or environmental factors that make some crops more attractive or vulnerable to pests.

The relationship between AEZ and Pest Count shows a mild positive correlation (r = 0.31), suggesting that specific agroecological zones such as UH2 experience higher pest incidence. This may be influenced by climatic conditions, elevation, or vegetation patterns that favor pest proliferation.

Lastly, there is a mild negative correlation between AEZ and Health Index (r = −0.28), indicating that crops grown in higher elevation zones may experience more stress, potentially due to harsher environmental conditions or limited resource availability.

Mean pest count by subcounty

This analysis compares mean pest pressure across six sub counties in Nyeri County using field data from 120 farms. A one-way ANOVA revealed a statistically significant difference in pest counts among sub counties ($p < 0.001$). Tukey's Honest Significant Difference (HSD) test was applied to classify sub counties into statistically homogeneous groups.

The results show that Mathira East had the highest pest pressure (mean = 2.31) and was assigned to group 'a', indicating significantly higher pest incidence than Tetu, Othaya, and Nyeri Town, which were grouped under 'b'. Mukurweini and Kieni East fell into group 'ab', suggesting intermediate pest levels not significantly different from either group. These groupings provide a statistical basis for prioritizing pest management interventions (Table 7).

Table 7. Mean pest count by sub county grouping

Subcounty	Mean pest count
Mathira east	2.31a
Mukurweini	1.76ab
Kieni east	1.83ab
Othaya	1.64b
Tetu	1.49b
Nyeri town	1.40b
HSD ($\alpha = 0.05$)	0.67
ANOVA p-value	< 0.001

Sub counties sharing the same letter are not significantly different at $\alpha = 0.05$. HSD is the minimum mean difference required for significance.

Pairwise comparisons of pest pressure between subcounties

To identify specific differences in pest pressure between subcounties, pairwise comparisons were conducted using Tukey's HSD post hoc test. The critical HSD value was calculated at 0.67 for $\alpha = 0.05$. Comparisons revealed that Mathira East had significantly higher pest counts than Nyeri Town (p= 0.009), Tetu (p= 0.014), and Othaya (p= 0.049). Differences with Mukurweini (p= 0.061) and Kieni East (p= 0.072) were not statistically significant (Table 8).

These results reinforce the grouping structure and highlight Mathira East as a pest hotspot requiring targeted interventions. The statistical evidence supports spatially differentiated pest management strategies across Nyeri County.

Table 8. Pairwise comparison of pest pressure

Comparison	Mean difference	HSD critical value	p-value
Mathira east vs Nyeri town	0.91	0.67	0.009
Mathira east vs Tetu	0.82	0.67	0.014
Mathira east vs Othaya	0.67	0.67	0.049
Mathira east vs Mukurweini	0.55	0.67	0.061
Mathira east vs Kieni east	0.48	0.67	0.072
Mukurweini vs Nyeri town	0.36	0.67	0.478
Othaya vs Nyeri town	0.24	0.67	0.732
Tetu vs Nyeri town	0.09	0.67	0.982

Significant differences occur when the mean difference exceeds the HSD value and $p < 0.05$. Comparisons involving Mathira East show the most pronounced pest pressure disparities

Pest management practices and farmer knowledge of application rates

This subsection presents the pest control strategies adopted by 128 farmers in Nyeri County and evaluates their perceived effectiveness. Farmers reported using a range of methods including chemical, cultural, biological, and integrated approaches. Each respondent rated the effectiveness of their chosen method on a scale from 1 (ineffective) to 5 (highly effective) (Table 9).

The most widely adopted method was synthetic chemical pesticides, used by 83% of respondents. However, despite its popularity, the average effectiveness rating was moderate (mean = 3.6). Critically, 62% of chemical pesticide users reported not understanding the correct dosage or application rate, which likely contributes to reduced efficacy, increased pest resistance, and environmental risks.

Integrated Pest Management (IPM), though used by only 29% of farmers, received the highest effectiveness rating (mean= 4.3), suggesting that training and awareness significantly improve outcomes. Biological control methods also performed well, while cultural and mechanical practices were widely used but rated lower in effectiveness. A small proportion of farmers (11%) reported using no pest control measures, resulting in the lowest effectiveness scores.

Table 9. Pest management practices and reported effectiveness (n = 128)

Pest management practice	Farmers using (%)	Mean effectiveness (1–5)	Standard deviation (SD)	Coefficient of variation (CV)	Dosage understanding (Synthetic pesticides)
Chemical pesticides (synthetic)	83%	3.6	0.9	0.25b	62% do not understand dosage
Cultural practices (e.g., weeding, crop rotation)	68%	3.2	1.1	0.34c	Not applicable
Biological control (e.g., neem, biopesticides)	41%	3.8	0.7	0.18ab	Not applicable
Mechanical control (e.g., handpicking, traps)	36%	2.9	1.0	0.34c	Not applicable
Integrated Pest Management (IPM)	29%	4.3	0.6	0.14a	Not applicable
Botanical extracts (e.g., chili, garlic)	22%	3.5	0.8	0.23b	Not applicable
No control measures used	11%	1.8	0.5	0.28d	Not applicable

Effectiveness was rated by farmers on a scale from 1 (ineffective) to 5 (highly effective). Grouping letters (a–d) indicate statistically significant differences in effectiveness based on Tukey's HSD test (α = 0.05). The column "Dosage Understanding" reflects the proportion of farmers using synthetic pesticides who reported not knowing the correct amount to apply. This knowledge gap highlights the need for targeted extension services and farmer education programs.

DISCUSSION

Pest pressure across agro-ecological zones (AEZs)

The study revealed marked variation in pest pressure across agro-ecological zones in Nyeri County, with the Upper Highland Zone (UH2) exhibiting the highest pest diversity and the lowest mean crop health index (2.73). In contrast, LH3 recorded relatively healthier crops (mean = 3.15), while UM3 showed reduced diversity but noticeable pest dominance. This confirms that ecological gradients strongly influence pest population dynamics and crop stress.

These findings are consistent with Okonjo *et al.* (2018), who reported that highland zones in Kenya experience elevated pest pressure due to cooler temperatures, higher humidity, and continuous cropping systems, which favor pest survival and rapid reproduction. CABI (2018) similarly emphasized that cropping intensity, host plant availability, and microclimatic stability create ideal ecological niches for insect pests, particularly in high-altitude farming systems such as those in UH2.

The high Shannon index (3.19) and Simpson index (0.95) recorded in UH2 reflect a complex and stable pest community, suggesting that pest species coexist without a single dominant taxon. Gitonga *et al.* (2020) noted that such ecological richness is common in intensive horticultural regions, where crop diversity and year-round cultivation sustain multiple pest life cycles. This complexity makes pest suppression more difficult and highlights the necessity of AEZ-specific surveillance and control strategies rather than generalized approaches.

Relationship between pest count and crop health

The regression analysis confirmed a statistically significant inverse relationship between pest count and crop health (β = −0.45; $p < 0.001$), meaning that each additional pest recorded per farm reduced the crop health index by nearly half a unit. With $R^2 = 0.38$, pest pressure alone explains a substantial proportion of crop health variability, demonstrating its central role in determining farm productivity.

The additional negative coefficients for UH2 (−0.32) and UM3 (−0.61) further show that ecological conditions amplify pest damage. This supports CEJAD (2019), who reported that pest infestations are among the leading causes of yield losses in smallholder systems, particularly where pest management is inconsistent or poorly timed.

Nderitu *et al.* (2017) similarly found that pest burden was a key predictor of reduced crop performance in central Kenya, especially in zones with limited access to extension services. The strong negative correlation between pest count and crop health (r = −0.62) further validates this relationship and emphasizes that pest management is not optional but essential for crop sustainability.

Pest diversity and distribution

A total of 33 insect pest taxa were identified, demonstrating a highly complex pest landscape. Aphids

(38), thrips (22), and armyworms (15) were the most prevalent, especially in UH2 and LH3. This concentration reflects favorable climatic conditions and overlapping cropping cycles that support continuous pest reproduction.

Plantwise (2019) reported similar patterns in highland regions, noting that overlapping host plants and favorable moisture regimes increase pest-host interactions. The coexistence of multiple pest species within the same AEZ increases crop vulnerability, as farmers are often forced to manage several pests simultaneously.

Karanja *et al.* (2021) emphasized that such diversity necessitates integrated ecological surveillance systems, as single-pest strategies are ineffective in complex ecosystems. The presence of rare pests in UM3 further suggests localized crop-pest interactions that require targeted monitoring.

Crop vulnerability to pest pressure

Cabbage, kales, and maize recorded low health indices (3.1, 2.0, and 1.8) and high variability (CV up to 0.41), making them the most vulnerable crops. These results indicate not only susceptibility but also instability across farms, reflecting inconsistent pest control outcomes.

Wainaina *et al.* (2020) reported that brassicas and cereals are highly attractive to pests due to soft tissues and high nitrogen content. This biological susceptibility explains their high pest loads and poor health performance in Nyeri.

Conversely, tea and banana recorded the highest health indices (4.2 and 4.0) and lowest CVs, suggesting resilience and stable productivity. FAO (2021) similarly observed that perennial crops experience lower pest damage due to tougher foliage, structured management, and biological buffering. These findings highlight the importance of crop-specific pest management protocols.

Sub-county spatial variation in pest pressure

The ANOVA and Tukey tests revealed significant spatial variation, with Mathira East (mean= 2.31) recording the highest pest pressure, significantly exceeding Nyeri Town, Tetu, and Othaya. This confirms that pest burden is not evenly distributed across the county.

CEJAD (2019) attributed such intra-county variation to differences in microclimate, cropping intensity, and pesticide use. Muriuki *et al.* (2022) further demonstrated that land use patterns and access to pest control services strongly influence pest distribution.

Kenya's Migratory and Invasive Pests Strategy (2022–2027) emphasizes that pest outbreaks follow ecological gradients and human activity patterns, reinforcing the need for spatially targeted interventions rather than county-wide uniform policies.

Pest management practices and effectiveness

Although 83% of farmers used chemical pesticides, the moderate effectiveness score (3.6) and the fact that 62% did not understand dosage reveal major inefficiencies. Okonjo *et al.* (2018) similarly reported that misuse accelerates resistance and reduces control success.

IPM, despite low adoption (29%), recorded the highest effectiveness (4.3), supporting FAO (2021), who advocates IPM as a sustainable solution. Biological methods also performed well, consistent with CEJAD (2019), who promoted low-toxicity alternatives.

Cultural and mechanical practices were less effective, echoing Wainaina *et al.* (2020), who noted that traditional methods alone cannot manage high pest pressure.

Implications for extension and policy

The results demonstrate that pest management in Nyeri must be ecologically targeted, crop-specific, and knowledge-driven. Extension programs should prioritize IPM training, safe pesticide use, and biological control promotion, especially in UH2 and Mathira East.

This aligns with Kenya's agricultural policy framework and FAO (2021), which emphasize decentralized, farmer-led pest management systems.

CONCLUSION

This study demonstrates that insect pest pressure in Nyeri County is strongly shaped by agro-ecological conditions, crop type, and farmer management practices. Pest incidence and diversity varied significantly across agro-ecological zones, with the Upper Highland zone (UH2) emerging as a clear hotspot characterized by the highest pest diversity and the lowest crop health indices. These findings confirm that altitude-related microclimatic factors and intensive cropping systems play a central role in driving pest outbreaks in highland farming environments.

A strong inverse relationship between pest pressure and crop health was consistently observed, indicating that increasing pest abundance directly compromises crop vigor and productivity. Crops such as cabbage, kales, and maize were identified as the most vulnerable, exhibiting high pest loads and low, highly variable health indices. In contrast, perennial and semi-perennial crops including tea, banana, and apple showed greater resilience, likely due to inherent crop traits, structured management systems, and lower susceptibility to multiple pest complexes.

Marked spatial variation was also evident at the sub-county level, with Mathira East recording significantly higher pest pressure than other sub-counties. This spatial heterogeneity highlights the limitations of uniform, county-wide pest control approaches and underscores the importance of localized, evidence-based interventions.

Although synthetic pesticides were the dominant pest control method, their effectiveness was constrained by widespread knowledge gaps regarding correct application rates. In contrast, Integrated Pest Management (IPM), despite limited adoption, achieved the highest effectiveness ratings, demonstrating its potential as a sustainable and reliable pest control strategy.

RECOMMENDATIONS

Based on the findings of this study, several actionable recommendations are proposed to enhance pest management effectiveness and sustainability in Nyeri County.

Strengthen farmer training on pesticide use

Targeted agricultural extension programs should be implemented to improve farmers' knowledge of safe and effective pesticide application, with particular emphasis on correct dosage, timing, and resistance management. Addressing these knowledge gaps will improve control efficacy, reduce production costs, and minimize environmental and human health risks associated with pesticide misuse.

Promote integrated pest management (IPM)

The adoption of Integrated Pest Management should be scaled up through farmer field schools, demonstration plots, and training workshops. Given its high effectiveness rating despite limited uptake, IPM offers a sustainable approach that combines biological, cultural, and chemical methods to reduce pest pressure while conserving beneficial organisms and ecosystem services.

Implement agro-ecological zone–specific pest surveillance

County-level pest monitoring systems should be established and tailored to distinct agro-ecological zones, with priority given to high-risk areas such as the Upper Highland zone and pest hotspots like Mathira East. Early warning systems and regular surveillance will enable timely, targeted interventions and reduce the likelihood of widespread outbreaks.

Encourage crop diversification and improved cultural practices

Farmers should be supported to adopt crop rotation, intercropping, and diversification strategies that disrupt pest life cycles and reduce host availability, particularly for highly susceptible crops such as cabbage, kales, and maize. These practices can complement chemical and biological controls while enhancing overall farm resilience.

Enhance access to biological and botanical pest control options

The availability and use of biopesticides and botanical extracts (e.g., neem, chili, and garlic-based products) should be improved through market support, certification, and extension outreach. These alternatives offer environmentally friendly options that can reduce dependence on synthetic pesticides when integrated appropriately.

Integrate pest management into climate-smart agriculture and policy planning

Pest management strategies should be incorporated into broader climate-smart agriculture frameworks and county-level agricultural policies. Allocating resources based on spatial pest pressure data will improve the efficiency of interventions and support long-term sustainability in highland farming systems.

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