

Article

The Influence of Ecological Pest Management Practices on Pests and Natural Enemies Under a Cabbage–Garden Pea Rotational System in Central Kenya

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Abstract

Pest pressure is a major constraint on crop production in Sub-Saharan Africa, where small-holder farmers rely heavily on synthetic pesticides with potential environmental and health risks. Ecological pest management practices (EPMs) have been proposed as sustainable alternatives, although field-based evidence is limited. This study evaluated pest and natural-enemy responses to EPMs in a cabbage–garden pea rotation system over six years (2020–2025) in Central Kenya. Four treatments were assessed: homemade botanical extracts (Botanicals), coriander intercropping (Intercrop), botanical extracts combined with coriander intercropping (Botanicals + Intercrop), and a control. In cabbage, ecological treatments often recorded lower aphid and diamondback moth abundance and damage than the Control, although these patterns were not consistently significant. Aphid cumulative abundance ranged from an Area Under Disease Progress Curve (AUDPC) of 128.0 under the Control to 47.5 under Botanicals + Intercrop, while DBM abundance ranged from 68.5 to 20.0. In garden pea, aphid damage ranged from an AUDPC of 39.3 under Intercrop to 25.1 under Botanicals + Intercrop, while cutworm damage ranged from 56.3 under Botanicals to 14.8 under Intercrop. Significant treatment effects were detected for selected pest responses. Shannon diversity differed significantly among the treatments in both crop phases. As such, responses were pest- and season-specific rather than uniformly suppressive. These findings identify companion cropping and botanical applications as promising components of EPM within the treatments evaluated. Comparison with conventional pesticide-based or farmer-practice management is however required before recommendations for substitution or wider adoption can be made.

Keywords: agroecology; ecological intensification; sustainable alternatives; organic agriculture; sub-Saharan Africa



Academic Editor: Piotr Prus

Received: 24 June 2026

Revised: 18 July 2026

Accepted: 24 July 2026

Published: 28 July 2026

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1. Introduction

Globally, pests and diseases cause losses of up to 40% of crop yields annually, resulting in economic costs exceeding USD 220 billion, of which invasive insects account for at least USD 70 billion [1]. For many smallholder farmers in Sub-Saharan Africa, synthetic inputs remain the most accessible means of addressing pest and disease pressures and

achieving stable yields [2]. However, their continued use has been associated with adverse environmental impacts, including loss of biodiversity through disruption of beneficial soil organisms and arthropods, soil degradation through nutrient mining and acidification, contamination of freshwater bodies through runoff and human health risks [3]. In Kenya, this is particularly more pronounced in high-value vegetables like cabbage (*Brassica oleracea* var. *capitata*) and garden pea (*Pisum sativum*), which are widely grown by close to 20 million smallholder farmers [4]. These challenges have prompted increased attention to agroecological strategies that can deliver sustainable pest regulation and support biodiversity in vegetable and legume systems, while sustaining yield production [5,6].

Ecological pest management practices (EPMs) such as homemade botanical extracts, companion cropping and crop rotation are increasingly recognized for their potential to regulate pests while minimizing environmental harm [6]. Importantly, locally prepared botanicals and habitat-based interventions potentially provide smallholder farmers with accessible, low-input pest management options that rely on locally available materials rather than proprietary inputs [7]. When appropriately implemented, empirical evidence demonstrates that these practices can achieve pest regulation comparable to synthetic or commercial biopesticides without the associated financial and ecological burdens [5].

Botanicals derived from plants such as neem (*Azadirachta indica*), garlic (*Allium sativum*), chili pepper (*Capsicum frutescens*), *L. camara* and Mexican marigold (*Tagetes erecta*) have shown efficacy in managing pests while being biodegradable and safer for non-target species [5,6]. In cabbage and garden pea, these interventions target key pests including aphids (*Brevicoryne brassicae*), diamondback moth (DBM) (*Plutella xylostella*), cabbage looper (*Trichoplusia ni*), pea weevils (*Bruchus pisorum*) and pod borers (*Helicoverpa armigera*). In Kenya, DBM alone has been shown to cause about 30–90% yield losses in farmer-managed cabbage fields [8]. Habitat manipulation through companion cropping with beneficial attracting plants such as coriander (*Coriandrum sativum*) further supports ecological balance by attracting beneficial arthropods such as ladybirds (*Coleoptera: Coccinellidae*), hoverflies (*Diptera: Syrphidae*), lacewings (*Chrysoperla carnea*) and parasitoid wasps that help regulate pest populations [9,10]. When integrated with botanical applications, habitat manipulation through companion cropping using beneficial attracting plants can operate synergistically by combining direct pest deterrence with enhanced biological control [11].

While botanical pesticides and habitat manipulation are widely promoted as complementary components of ecological pest management, the ecological interactions between these approaches remain poorly understood. Botanical formulations can directly suppress herbivorous pests, but concerns persist regarding their potential effects on natural enemies and the extent to which they influence biological control processes under field conditions [5,7]. Likewise, companion cropping can enhance predator and parasitoid abundance through provision of floral resources and habitat complexity, but increases in natural enemy populations do not always translate into effective pest suppression [9,12]. Consequently, it remains unclear whether combining botanical applications with habitat diversification generates synergistic effects that strengthen pest regulation, merely additive effects, or antagonistic interactions that diminish the contribution of natural enemies.

Although botanical pesticides and companion cropping have each been studied extensively [5,8,9,13,14], less is known about their combined performance under repeated field application. Their joint use may produce additive, complementary or antagonistic responses, particularly where botanical applications affect both pests and beneficial arthropods and where companion plants alter the field environment. Evidence is especially limited for rotational systems in which crop identity, pest assemblages and natural-enemy communities change between seasons. Most available studies have evaluated botanical applications or habitat diversification independently, over short periods and within single

crops [5,13,14]. It is therefore still uncertain whether combining these practices provides greater or more consistent pest regulation than either practice alone and whether the response is maintained across successive vegetable and legume phases.

The novelty of this study is the factorial evaluation of botanical application and coriander intercropping, both separately and in combination, over multiple seasons within a cabbage–garden pea rotation. The study simultaneously assessed pest abundance, crop damage, cumulative pest pressure, natural-enemy abundance and Shannon diversity. This allowed the independent and interactive effects of the two practices to be evaluated separately within the cabbage and garden pea phases of the rotation. The objective was to determine the individual and combined effects of botanical applications and coriander intercropping on pest abundance, crop damage and natural-enemy communities in a multi-season cabbage–garden pea rotational system in Central Kenya. We hypothesized that botanical application, companion cropping and their interaction would significantly influence cumulative pest abundance and damage, and that EPM treatments would significantly influence natural-enemy diversity.

2. Materials and Methods

2.1. Study Area Description

We conducted the study in Mwarano primary school in Kangari area, Murang'a County, Kenya, within the framework of the Long-Term Farming Systems Comparison Trial (SysCom) (<https://systems-comparison.fibl.org/>, accessed on 23 July 2026). This region is within the central highlands of Kenya that experience a cool and humid climate [15]. The soils are deep and well-drained, characterized by a red to red-brown colour and sandy clay loam texture [16]. The trial site is located at approximately 1980 m [17] at S 0.779465, E 36.856537.

The rainfall pattern was bimodal, with the long rains (LR) occurring between March and May, and the short rains (SR) between October and December. During the experimental period, seasonal cumulative rainfall varied considerably among years and between rainfall seasons (Figure 1). The wettest seasons were SR2020 (1666.5 mm), SR2024 (1408.5 mm) and LR2024 (1379.8 mm), indicating high rainfall during these years. In contrast, the driest season was SR2022 (513.5 mm), while SR2025 (820.8 mm) and LR2021 (820.0 mm) experienced comparatively low rainfall totals, reflecting below-average moisture conditions. Temperatures ranged from 10 °C to 25 °C, which is well-suited for production of legumes and brassicas [15].

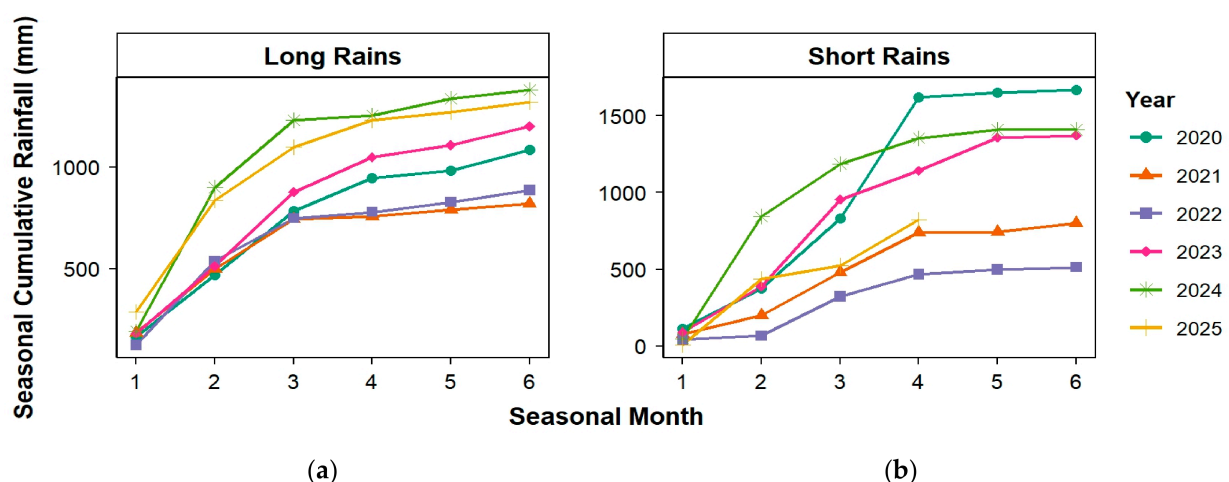


Figure 1. Seasonal cumulative rainfall patterns observed during the study period (2020–2025) in Kangari, Murang'a County, Kenya. (a) Long Rains (LR) cumulative rainfall by seasonal month for each study year. (b) Short Rains (SR) cumulative rainfall by seasonal month for each study year, highlighting interannual variation in rainfall accumulation.

2.2. Experimental Design and Ecological Pest Management Practices

We implemented the field experiment in a Randomized Complete Block Design (RCBD) for twelve continuous cropping seasons, from 2020 to 2025. Cabbage (Pruktor F1) was the test crop during long rains (LR) seasons, while garden pea (Kelplus Vuna) was the test crop during short rains (SR) seasons. We applied four pest treatments: (i) Homemade botanical (Botanicals); (ii) companion cropping with coriander (Intercrop); (iii) a combination of botanicals and intercrop (Botanicals + Intercrop); and (iv) untreated control receiving neither botanical applications nor companion cropping (Control). The experiment comprised 16 permanent experimental plots corresponding to four treatments replicated within four blocks. Each plot measured 3.5 m × 3.5 m (12.25 m²), giving a total experimental area of 196 m² excluding buffer spaces between plots. Crops were spaced at 50 cm intervals for cabbage and 45 cm intervals for garden pea, which allowed 49 plants per plot.

In the Intercrop and Botanicals + Intercrop treatments, coriander was established as a companion crop to provide floral resources and habitat for beneficial arthropods while potentially disrupting pest host location. Coriander was sown approximately two weeks prior to planting of cabbage or garden pea to ensure that flowering coincided with periods of peak pest and natural enemy activity. The intercrop was established uniformly throughout the plot by sowing coriander between crop rows while maintaining the standard crop spacing for cabbage and garden pea. Coriander plants were maintained throughout the cropping season and were not removed after flowering. Routine weeding was carried out manually to minimize competition with the main crop while preserving the companion crop stand. Coriander flowering commenced approximately six to eight weeks after sowing and continued through much of the crop growing period, thereby providing nectar and pollen resources for predators, parasitoids and pollinators.

We managed soil fertility of the plots similarly. All nutrient rates were determined by converting the recommended nutrient requirements for each crop into plot-level quantities based on the experimental plot size and the nutrient concentrations of compost, Tithonia and rock phosphate. Compost and rock phosphate were applied at planting, supplying nitrogen at 45 kg ha⁻¹ N and phosphorus at 27 kg ha⁻¹ P. For cabbage, each plot received 6.7 kg of compost and 440 g rock phosphate. For garden peas, each plot received 9.5 kg compost and 547 g rock phosphate. Tithonia green biomass was applied as a top-dressing during early vegetative growth, at 22 kg per cabbage plot and 9.4 kg per garden pea plot. This nutrient management regime was followed by routine weeding and all other crop husbandry operations, which were implemented uniformly across treatments. Pest management interventions differed according to treatment assignment, with botanical sprays applied only in the Botanicals and Botanicals + Intercrop treatments, while the Control and Intercrop treatments received no pesticide applications throughout the study period. A conventional insecticide treatment was not included in the experimental design because the primary objective of the study was to evaluate the individual and combined effects of EPM practices on pest and natural enemy dynamics within a smallholder agroecological production system. The experiment was therefore designed to compare the relative performance of the tested ecological treatments against an untreated control and not to assess their equivalence or superiority to conventional pesticide-based or farmer-practice management.

Application of botanical extracts in the Botanicals and Botanicals + Intercrop treatments was guided by routine fortnightly pest scouting. Botanical sprays were initiated following the detection of economically relevant pest infestations during crop establishment and were subsequently repeated at approximately two-week intervals throughout the cropping season when pest populations persisted. The same decision criteria were applied across seasons and treatments receiving botanical applications. Formal economic threshold values were not used because the objective of the study was to evaluate the performance of

farmer-applicable EPM practices under practical smallholder field conditions rather than threshold-based intervention strategies.

The botanical formulation comprised 400 g of fresh *Tagetes minuta* leaves, 400 g of fresh *Lantana camara* leaves, 200 g of fresh *Allium sativum* bulbs, 200 g of fresh *Capsicum frutescens* fruits and 100 g of *Azadirachta indica* cake powder, corresponding to a fresh-weight ratio of 4:4:2:2:1. Plant materials were obtained locally and prepared immediately prior to extraction. Only fresh, healthy plant material free from visible disease or senescence symptoms was used for extraction. The leaves were chopped into small pieces, while garlic bulbs and chili fruits were crushed into a fine paste before mixing. The plant materials were immersed in 2 L of clean water at ambient temperature and allowed to steep for 24 h to produce an aqueous extract with an approximate stock concentration of 0.65 g mL⁻¹. Clean water from a single source was used for all extractions throughout the experiment. The formulation followed the 24-h PE + N preparation protocol chemically characterized by Munyoki et al. [6]. Their analysis identified phenolic, flavonoid, terpenoid and organosulfur constituents in the formulation using spectrophotometry and LC–MS. In the present field experiment, however, extract pH and concentrations of specific active compounds, including azadirachtin, allicin and capsaicin, were not independently quantified. The formulation was therefore standardized operationally through fixed plant-material quantities, a constant fresh-weight ratio, extraction volume, 24 h steeping period, filtration procedure and immediate preparation before field application.

Following extraction, the mixture was filtered through a fine mesh cloth before application. No detergent or surfactant was added to the extract. Extracts were prepared immediately before application and used on the day of filtration to minimize degradation of bioactive compounds and variation associated with storage. This formulation was selected to represent a preparation that smallholder farmers could produce using locally available plant materials and water without additional purchased inputs. The application volume was estimated using a standard high-volume knapsack spray rate of approximately 500 L ha⁻¹, equivalent to about 175 mL per 3.5 m² plot. Spraying was carried out to achieve uniform foliar coverage while avoiding visible runoff.

2.3. Data Collection and Management

The experiment employed four replicated blocks and repeated measurements collected over 10 cropping seasons, resulting in substantial temporal and spatial replication that increased the precision of treatment effect estimates and the ability to detect biologically meaningful differences among treatments. To monitor the influence of the EPMs, pest populations, pest damage and natural enemy abundance were assessed fortnightly throughout each cropping season, beginning two weeks after crop establishment and continuing until crop maturity and harvest. Depending on crop duration and seasonal conditions, this resulted in approximately five to seven assessment rounds per season for both cabbage and garden pea. Consequently, observations captured pest and natural enemy dynamics across the major crop growth stages, including early vegetative growth, canopy development, flowering and reproductive stages. During each scouting episode, 20 plants were assessed per plot. Each plot was divided into four quadrants to ensure spatial representation of pest and natural enemy distributions within plots. Five plants were randomly selected from each quadrant during every sampling event, resulting in 20 sampled plants per plot, 80 plants per block and 320 plants assessed during each monitoring episode across the experiment. The sampling intensity represented approximately 41% of all plants within each plot and was considered sufficient to capture within-plot variability while remaining operationally feasible for repeated fortnightly assessments over multiple seasons.

Pest abundance was determined through direct visual identification and counting of individual pests on each sampled plant. To reduce observer-related and temporal variation, monitoring was conducted by the same trained field personnel throughout the study using a standardized observation sheet and identification guide. Before data collection, observers were trained in plant selection, pest and natural-enemy identification, counting procedures and application of the damage severity scale. Assessments were conducted during a consistent daylight period, and all 16 plots were evaluated on the same day during each sampling episode. A uniform inspection procedure and approximately equal observation time per plant were maintained across plots and treatments. Assessments were conducted under suitable field conditions and were postponed during rainfall, strong winds or when foliage was excessively wet, as these conditions could reduce arthropod visibility and activity. The order in which plots were assessed was rotated across sampling episodes to limit systematic bias associated with time of day.

Mean pest abundance was subsequently calculated for each treatment and sampling period. Relative abundance of each pest species was determined separately for community composition analyses by expressing the abundance of a given species within a treatment as a proportion of the total abundance recorded for that species across all treatments during the sampling period. Damage assessments were not initially recorded using a single scoring approach across all pest groups. During field data collection, damage caused by DBM, cabbage webworm and cabbage looper was assessed directly using a five-point ordinal severity scale, whereas damage caused by the remaining pest groups was recorded as the percentage of affected plant tissue relative to the whole plant. To ensure comparability across pest taxa and permit uniform statistical analysis, percentage damage values were subsequently converted to an equivalent five-point severity scale during data processing. The scale ranged from 1 to 5, where 1 represented no visible damage; 2 represented slight damage, affecting less than 25% of plant tissue; 3 represented moderate damage, affecting approximately 25–50% of plant tissue; 4 represented extensive damage, affecting approximately 51–75% of plant tissue; and 5 represented severe damage, affecting more than 75% of plant tissue or causing substantial loss of plant vigour. The scoring system was adapted from Hasheela et al. [18] and applied consistently across aphids, cutworms, diamondback moth and whitefly assessments to facilitate comparison of damage progression among treatments and seasons.

Natural enemies were assessed on the same 20 plants selected for pest observations during each fortnightly sampling episode. The sampling area was standardized across treatments by assessing the same number of plants in every plot. Five randomly selected plants were examined in each of the four plot quadrants, giving 20 plants per plot and 320 plants across the experiment during each sampling episode. Surveys were conducted during a consistent daylight period, and all plots were assessed on the same day using the same plant-inspection sequence and comparable observation effort per plant. Assessments were avoided during rainfall, strong winds and excessive leaf wetness because these conditions could affect natural-enemy activity and detectability. The order of plot assessment was rotated between sampling episodes to reduce systematic time-of-day effects. Natural enemies were quantified exclusively through direct visual inspection of the sampled plants. Each selected plant was inspected systematically from the lower to the upper canopy, including the upper and lower leaf surfaces, stems, growing points, flowers and developing reproductive structures. Sweep netting, suction sampling and yellow sticky traps were not used because the study focused on arthropods directly associated with the crop canopy and required the same non-destructive sampling unit to be maintained for pest, damage and natural-enemy assessments. Visible individuals were counted without removing them from the plant.

Natural enemies were identified to the lowest taxonomic level that could be determined reliably under field conditions. *Aphidius colemani* was identified to species level, while hoverflies, ladybirds, lacewings and other parasitoid wasps were recorded at family, taxonomic-group or functional-group level where field identification to species was not reliable. Adult parasitoids were distinguished using observable morphological characteristics, including body form, wing venation, antennae and association with their host pest. Braconid parasitoids that could not be identified reliably to species were recorded as Braconidae. Counts represented directly observed adult natural enemies and did not constitute measurements of parasitism rates. Shannon diversity was calculated using counts of predatory and parasitoid taxa classified as natural enemies. Pollinators that did not have a recognized predatory or parasitoid function were recorded separately and excluded from the Shannon diversity calculations.

2.4. Statistical Analysis

All analyses were conducted in R version 4.5.2 [19]. Prior to analysis, data distributions were assessed using the Shapiro–Wilk test implemented in the stats package, while homogeneity of variances was evaluated using Levene’s test from the car package [20]. Variables exhibiting substantial departures from model assumptions were transformed using $\log(x + 1)$ transformations before analysis. Descriptive statistics were calculated for pest abundance, pest damage and natural enemy abundance across treatments and seasons.

Pest abundance was quantified using mean absolute abundance and cumulative seasonal pest pressure. Mean abundance was calculated as the average number of individuals recorded per sampled plant within each treatment and sampling period. Cumulative pest pressure was estimated using the area under the disease progress curve (AUDPC), which integrates repeated observations collected throughout the cropping season into a single measure of cumulative abundance over time. AUDPC values were calculated using the trapezoidal integration method described by Campbell and Madden [21], as given in the formula

$$AUDPC = \sum_{i=1}^{n-1} \left(\frac{y_i + y_{i+1}}{2} \right) (t_{i+1} - t_i) \quad (1)$$

where

- y_i = pest abundance/damage at observation i ;
- y_{i+1} = pest abundance/damage at the next observation;
- $t_{i+1} - t_i$ = time interval between observations;
- n = total number of observations.

AUDPC calculations required at least two observation time points within a treatment–season combination. Where fewer than two observations were available because of crop failure, taxon absence or incomplete monitoring records, AUDPC values were considered non-estimable and were excluded from subsequent factorial analyses. Similarly, treatment–season combinations with insufficient observations to estimate variability were retained in descriptive summaries but were omitted from inferential analyses involving the affected variable. Missing values were not imputed, and all analyses were conducted using complete-case observations available for the respective response variable. Under normal sampling conditions, each treatment–season combination contributed observations from four replicated plots, each based on assessments of 20 plants per plot and approximately five to seven sampling rounds per season. Consequently, individual seasonal AUDPC estimates were generally derived from approximately 400 to 560 plant observations per treatment–season combination. Deviations from these numbers occurred only where crop failure, taxon absence or incomplete observations reduced the number of available records.

Treatment–season combinations excluded from particular analyses because of insufficient observations are identified in the corresponding tables using footnotes.

To evaluate EPM effects on pest abundance and damage, AUDPC values were first derived from repeated seasonal observations using the trapezoidal method. To evaluate EPM effects on cumulative pest abundance and damage, factorial linear mixed-effects models (LMMs) were fitted using botanical application (B), companion cropping (C), and their interaction ($B \times C$) as fixed effects, while Year and Block were included as random effects. Year accounted for repeated observations collected across seasons, whereas Block accounted for spatial variation associated with the randomized complete block design. This allowed the study to test whether Botanicals, Intercrop or Botanicals $\times$ Intercrop explained variation in cumulative pest abundance and damage across seasons:

$$AUDPC_{ijklm} = \mu + B_i + C_j + (BC)_{ij} + Year_k + Block_j + \varepsilon_{ijklm} \quad (2)$$

where:

- B_i represents botanical application;
- C_j represents companion cropping;
- BC_{ij} represents their interaction;
- $Year_k$ represents the random effect of year;
- $Block_j$ = random effect of block;
- ε_{ijklm} = residual error.

Type II ANOVA was performed using Wald F-tests derived from the mixed-effects models. Numerator degrees of freedom for the fixed effects were equal to one because both botanical application and companion cropping were binary treatment factors. Denominator degrees of freedom varied slightly among response variables depending on the number of available observations included in each model following exclusion of missing or non-estimable treatment–season combinations. Mean absolute abundance and damage values were summarized using means and standard errors. Natural enemy abundance was summarized descriptively by treatment and season. Shannon diversity was analysed using linear mixed-effects models with botanical application, companion cropping and their interaction specified as fixed effects and Year and Block as random effects.

The experiment was established as a long-term field trial in which the same treatment was maintained on the same experimental plots throughout the study period. Consequently, each plot retained its assigned management regime across years. This allowed cumulative ecological effects of repeated management practices to develop over time. Because cabbage and garden pea were assigned consistently to the LR and SR phases, respectively, crop identity and rainfall season were not treated as separable explanatory factors. Year was included as a random effect to account for interannual variation within each crop phase, but this did not separate crop effects from long-rain versus short-rain conditions. Statistical inference therefore focused on treatment effects within cabbage and garden pea, while differences between crop phases were interpreted cautiously. The use of mixed-effects models allowed the analysis to account for the hierarchical and repeated-measures structure of the long-term experiment while avoiding pseudo replication associated with repeated observations from the same blocks across years.

3. Results

3.1. Seasonal Abundance of Major Cabbage Pests Under Different EPM Treatments

Whereas a range of pest species were observed during the study period, aphids, cutworms and DBM were selected for detailed analysis because they consistently accounted for the largest proportion of pest abundance and crop injury across seasons, while the remaining

species occurred sporadically and at comparatively low abundances (Appendix A; Table A1). Aphid pressure varied noticeably across seasons, with the greatest cumulative infestation recorded in LR2020 and substantially lower pressure during the later seasons, particularly LR2023 and LR2025 (Figure 2A; Table A1). Several ecological treatments recorded lower numerical AUDPC values than the Control in individual seasons, particularly treatments containing Intercrop during the later seasons and Botanicals + Intercrop during the earlier seasons. However, neither Botanicals, Intercrop nor their interaction significantly influenced aphid abundance across seasons (Table A2). Cutworm populations also varied considerably among seasons, with pronounced fluctuations among treatments and years (Figure 2B). The factorial analysis detected significant effects of Botanicals ($p = 0.035$), Intercrop ($p = 0.050$) and the Botanicals $\times$ Intercrop interaction ($p = 0.016$), indicating that cutworm responses depended on both individual and combined ecological management practices (Table A2). DBM abundance was highest in LR2020 and generally lower thereafter (Figure 2C; Table A1). Although some ecological treatments recorded lower numerical values than the Control in particular seasons, neither the Botanicals effect, Intercrop effect nor their interaction was significant. Thus, the seasonal treatment differences in DBM abundance were not statistically consistent across the study period (Figure 2C; Table A1).

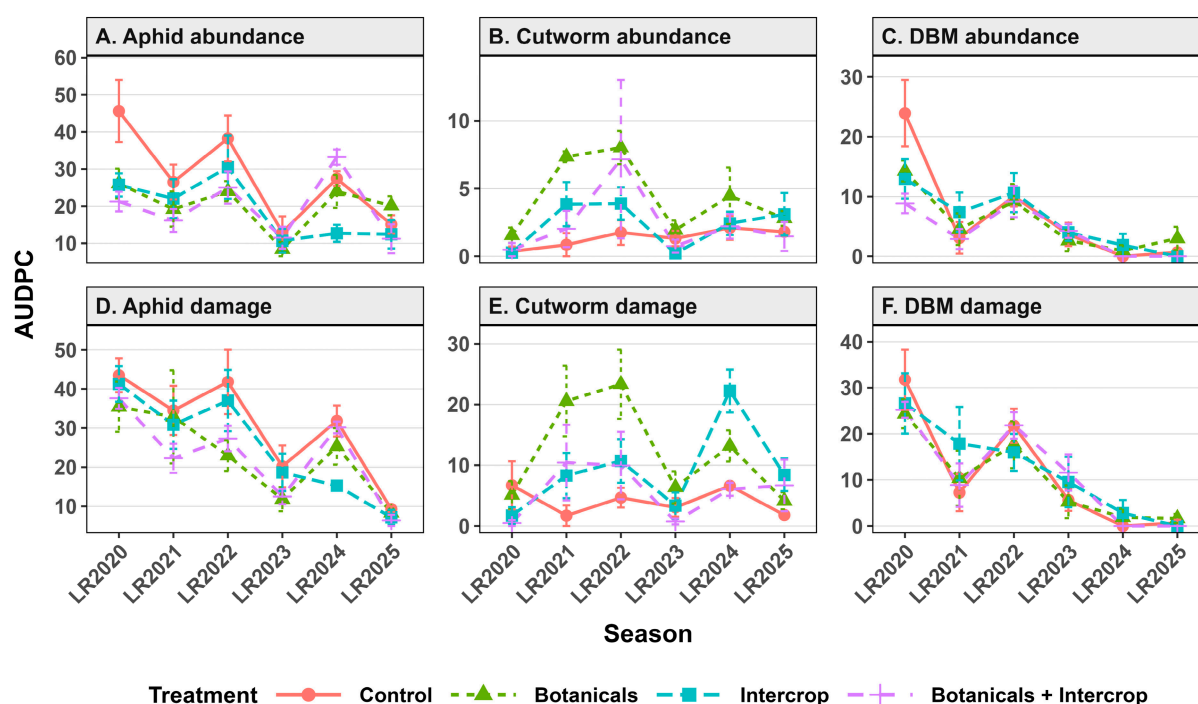


Figure 2. Seasonal cumulative abundance pressure and damage intensity (AUDPC) of major cabbage pests under EPM treatments from LR2020 to LR2025. Values represent seasonal AUDPC. Missing points denote treatment-season combinations for which AUDPC could not be estimated because of insufficient observations. (A) Seasonal cumulative aphid abundance. (B) Seasonal cumulative cutworm abundance. (C) Seasonal cumulative DBM abundance. (D) Seasonal cumulative aphid damage intensity. (E) Seasonal cumulative cutworm damage intensity. (F) Seasonal cumulative DBM damage intensity.

3.2. Seasonal Damage by Major Cabbage Pests Under Different EPM Treatments

Damage intensity varied considerably among seasons and ecological management treatments (Figure 2D–F; Table A3). Aphid damage differed significantly in relation to botanical application ($p = 0.010$), and a significant Botanicals $\times$ Intercrop interaction was also detected ($p = 0.031$; Table A4). Treatments containing Botanicals generally recorded lower cumulative aphid damage than the Control, although the significant interaction indicates that the mag-

nitude of the botanical effect depended on whether Intercrop was also present (Figure 2D). For cutworm damage, neither Botanicals nor Intercrop had a significant independent effect, but their interaction was significant ($p = 0.009$; Table A4). Botanicals + Intercrop recorded the lowest estimated cumulative damage, indicating that the response was associated with the treatment combination rather than with either practice independently (Figure 2E). DBM damage varied substantially among seasons (Figure 2F; Table A3). Some ecological treatments recorded lower numerical damage values than the Control in individual seasons, but no significant main or interaction effects were detected (Table A4).

3.3. Seasonal Abundance of Major Garden Pea Pests Under Different EPM Treatments

A range of pest species was observed during monitoring. However, aphids, cutworms and whiteflies were selected for detailed analysis because they were consistently the dominant pests across seasons, while other species occurred sporadically and at comparatively low abundances (Table A5). Aphid abundance was significantly associated with botanical application ($p = 0.001$), while the Botanicals $\times$ Intercrop interaction approached but did not reach significance ($p = 0.055$). Botanicals + Intercrop recorded the lowest estimated cumulative aphid pressure, and Intercrop alone the highest (Figure 3A; Table A5); however, the interaction pattern should be interpreted cautiously because it did not meet the predefined significance threshold (Table A6). Cutworm populations displayed pronounced treatment-dependent responses across seasons (Figure 3B). Cutworm abundance showed significant effects of Botanicals ($p = 0.024$) and Botanicals $\times$ Intercrop ($p < 0.001$). This indicated that the effectiveness of botanical applications depended strongly on cropping arrangement (Table A6). Intercrop alone recorded the lowest estimated cumulative pressure, whereas Botanicals + Intercrop recorded the highest (Figure 3B; Table A5). Whitefly abundance was significantly associated with Intercrop ($p < 0.001$) and the Botanicals $\times$ Intercrop interaction ($p = 0.029$), whereas Botanicals alone was not significant (Table A6). Treatments containing Intercrop generally recorded higher, rather than lower, cumulative whitefly abundance (Figure 3C; Table A5).

3.4. Seasonal Damage by Major Garden Pea Pests Under Different EPM Treatments

Aphid damage varied across seasons (Figure 3D; Table A7). Aphid damage was significantly associated with Botanicals ($p = 0.002$), whereas Intercrop and the Botanicals $\times$ Intercrop interaction were not significant (Table A8). Treatments receiving botanical applications generally recorded lower cumulative aphid damage than treatments without botanicals, indicating that the reduction in damage was associated primarily with botanical application rather than with treatment interactions. Cutworm damage was significantly associated with both Botanicals and Intercrop (both $p < 0.001$; Table A8), while their interaction was not significant. Intercrop alone recorded the lowest estimated damage, whereas Botanicals alone recorded the highest (Figure 3E; Table A7). The significant main effects therefore indicate variation associated with each practice but not necessarily a universally beneficial botanical response. Whitefly damage was significantly associated with Intercrop ($p = 0.001$), whereas Botanicals and the interaction were not significant (Table A8). Treatments containing Intercrop recorded higher cumulative whitefly damage than the Control and Botanicals treatments (Figure 3F; Table A7).

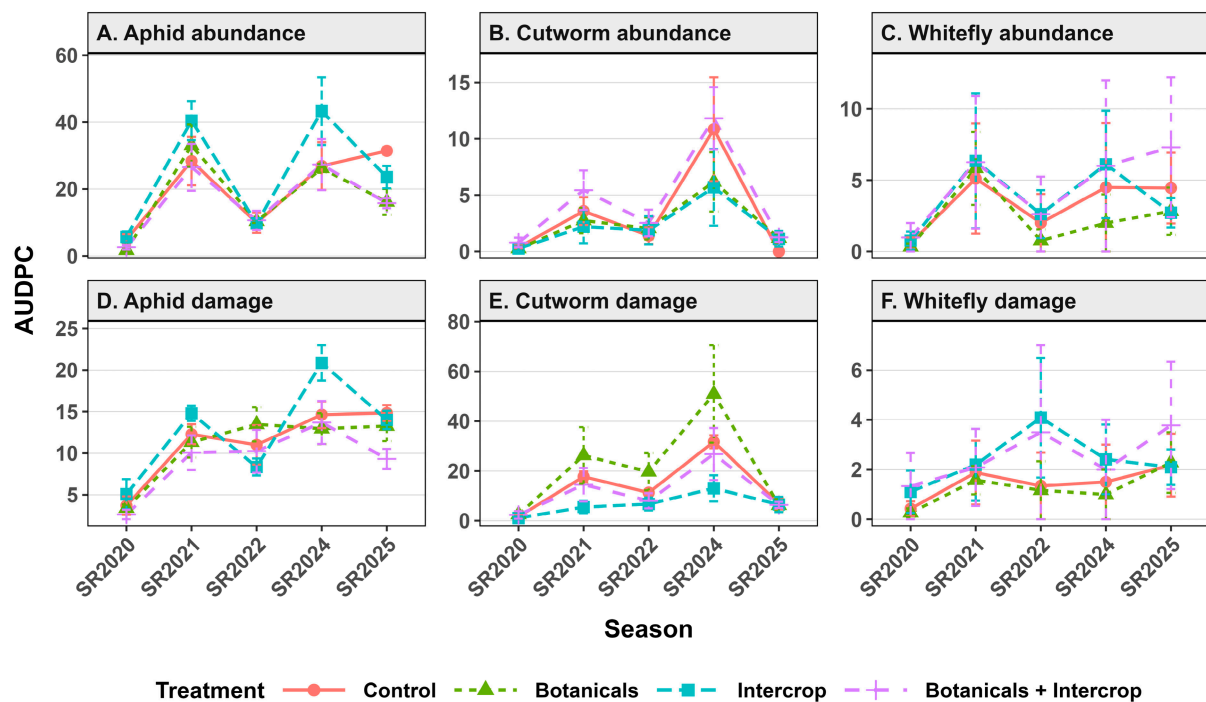


Figure 3. Seasonal cumulative abundance pressure and damage intensity of major garden pea pests under EPM treatments from SR2020 to SR2025. Values represent seasonal AUDPC. SR2023 was excluded because crop failure prevented reliable estimation of pest abundance and damage. Missing points denote treatment-season combinations for which AUDPC could not be estimated because of insufficient observations. (A) Seasonal cumulative aphid abundance. (B) Seasonal cumulative cutworm abundance. (C) Seasonal cumulative whitefly abundance. (D) Seasonal cumulative aphid damage intensity. (E) Seasonal cumulative cutworm damage intensity. (F) Seasonal cumulative whitefly damage intensity.

3.5. Shannon Diversity of Key Natural Enemies in Cabbage and Garden Pea Rotational Systems

Shannon diversity of key natural enemies varied across treatments and seasons in both cabbage and garden pea rotational systems (Figure 4; Table A9). In cabbage, Intercrop and Botanicals + Intercrop frequently recorded higher diversity values than Botanicals alone and the Control, particularly during LR2020, LR2021 and LR2022 (Figure 4A). Diversity values frequently exceeded 1.0 during the earlier seasons but declined during LR2023 and LR2025, indicating substantial interannual variation in natural-enemy community structure. In garden pea, diversity levels were more variable across seasons, with Control frequently recording the highest diversity during the earlier years, whereas Intercrop and Botanicals + Intercrop recorded the highest values in SR2025 (Figure 4B). Botanicals + Intercrop nevertheless maintained moderate to high diversity across both crop phases, while Botanicals alone often recorded lower values, particularly in SR2020 and SR2022. Analysis of variance confirmed a significant treatment effect on Shannon diversity in both cabbage ($F = 4.85$, $p = 0.004$) and garden pea ($F = 7.40$, $p < 0.001$) systems (Table A10).

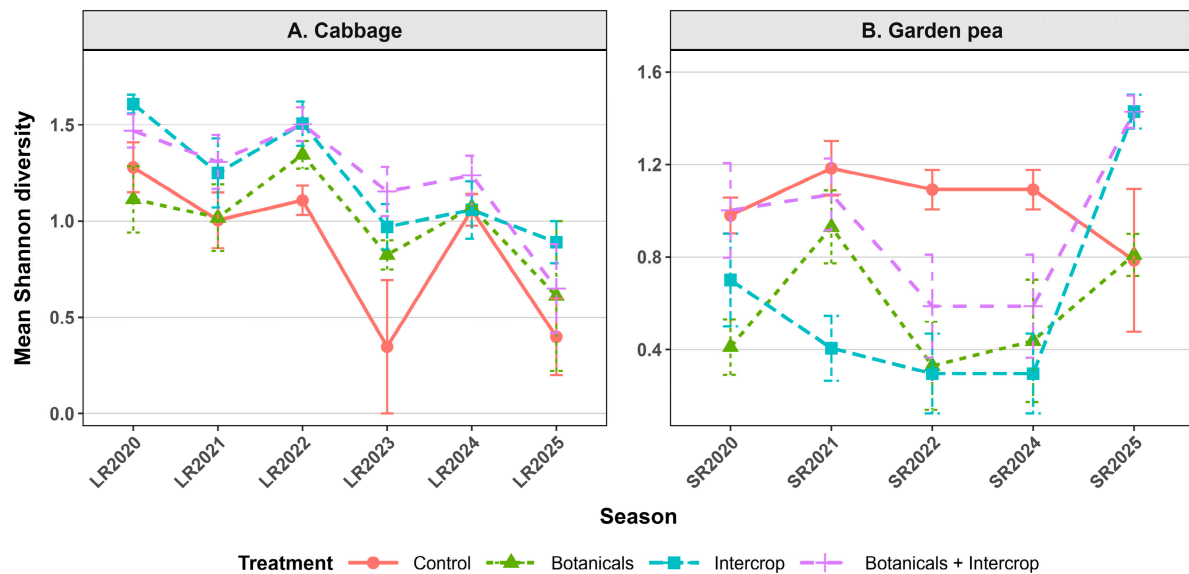


Figure 4. Seasonal Shannon diversity of natural-enemy communities under ecological pest management treatments in the cabbage and garden pea phases of the rotational system. Points represent mean Shannon diversity, and error bars represent standard errors. (A) Seasonal Shannon diversity of natural-enemy communities in cabbage during the LR seasons from LR2020 to LR2025. (B) Seasonal Shannon diversity of natural-enemy communities in garden pea during the SR seasons from SR2020 to SR2025. Garden pea diversity was not calculated for SR2023 because complete natural-enemy data were unavailable following crop failure during that season.

4. Discussion

In cabbage, several ecological treatments recorded lower numerical aphid abundance than the Control in individual seasons, although neither Botanicals, Intercrop nor their interaction significantly influenced aphid abundance. Aphids rely strongly on visual and olfactory cues for host location, suggesting that coriander intercropping may have disrupted host finding through increased vegetation complexity, while botanicals may have reduced feeding and settling behaviour rather than causing direct mortality. The absence of a strong treatment effect contrasts with studies reporting substantial aphid reductions under intercropping systems [5,13], and may reflect the highly variable rainfall conditions experienced during the study period in Central Kenya, where seasonal rainfall ranged from approximately 530 mm to 1661 mm. Such variability can alter aphid population growth, immigration rates and the persistence of botanical residues. In contrast, cutworm abundance was significantly influenced by Botanicals, Intercrop and their interaction, probably because this soil-dwelling and nocturnal pest responds more strongly to local habitat conditions and botanical residues near the soil surface than to host-location disruption alone [6,22]. DBM abundance showed lower numerical values under some treatments but no significant effects, differing from studies that reported stronger suppression through habitat diversification. This likely reflects the high mobility and immigration capacity of this specialist crucifer pest, whose ability to rapidly colonize brassica fields may reduce the effectiveness of local habitat manipulation, particularly under favourable climatic conditions [23].

Aphid damage was significantly influenced by Botanicals and the Botanicals $\times$ Intercrop interaction, suggesting that botanical efficacy depended on cropping arrangement rather than acting uniformly across treatments. This likely reflects the predominantly repellent, antifeedant and feeding-disruption properties of plant-derived compounds, which can reduce crop injury without necessarily causing large reductions in pest abundance [24]. The finding agrees with companion-planting studies in which aphid suppression was stronger when plant diversity was paired with other control pressures rather than used alone [25]. The stronger

response observed for damage than abundance further suggests that botanical treatments altered feeding behaviour more effectively than population density. Similarly, the significant interaction observed for cutworm damage indicates that combining Botanicals with Intercrop modified local ecological conditions in ways that single practices did not achieve, potentially through simultaneous effects on oviposition behaviour, soil microhabitat and exposure of larvae to natural enemies [6,22]. In contrast, although DBM damage was numerically lower under some ecological treatments and seasons, no significant treatment effects were detected. This differs from studies reporting stronger DBM suppression under habitat diversification and botanical management, and may reflect the high mobility, immigration capacity and specialist feeding behaviour of this crucifer pest, which reduce the effectiveness of local host-disruption mechanisms [26].

In garden pea, botanical application significantly influenced aphid abundance, probably because aphids are soft-bodied insects that are highly susceptible to contact toxicity and repellent secondary metabolites present in plant extracts [14]. The stronger response observed in garden pea compared with cabbage may indicate differences in crop architecture, aphid colonization patterns or microclimatic conditions influencing extract persistence and exposure. Similar observations have been reported in diversified cropping systems where single interventions produced weaker responses than integrated ecological management approaches [27]. Cutworm abundance was influenced by both Botanicals and the Botanicals $\times$ Intercrop interaction, although treatment responses were not uniformly beneficial, suggesting that soil-dwelling pests respond to complex interactions among canopy structure, microclimate, residue cover and natural enemy activity rather than to single interventions alone [13]. Whitefly abundance was significantly associated with Intercrop and the Botanicals $\times$ Intercrop interaction, although treatments containing Intercrop generally recorded higher cumulative values than treatments without Intercrop. This indicates altered pest pressure rather than improved control and suggests that whitefly responses depended on crop arrangement and its interaction with botanical applications rather than on direct botanical effects alone. This contrasts with studies reporting reduced whitefly infestations under crop diversification and suggests that increased canopy complexity may have created favourable humidity, shelter or resting conditions for this highly mobile canopy-dwelling insect [28]. The variable rainfall conditions experienced across seasons in Central Kenya may have further influenced whitefly population dynamics and the effectiveness of local habitat manipulation.

Aphid damage was significantly influenced by botanical application in garden pea, whereas neither Intercrop nor the interaction term was significant. This suggests that reductions in aphid injury were associated primarily with the direct effects of botanical extracts rather than with habitat diversification or synergistic interactions between practices. Aphids are highly susceptible to repellent and antifeedant secondary metabolites present in plant extracts, and reductions in feeding activity may occur even when population reductions are modest [29]. Cutworm damage was significantly influenced by Botanicals and Intercrop independently, but not by their interaction, indicating additive rather than synergistic effects and suggesting that the mechanisms underlying cutworm suppression operated largely through separate pathways. This agrees with evidence that the effectiveness of botanical extracts varies considerably among pest groups, feeding guilds and management contexts [29,30]. Whitefly damage, however, was influenced primarily by Intercrop rather than Botanicals, suggesting that crop diversification modified whitefly pressure indirectly through changes in habitat structure and microclimatic conditions rather than through direct toxic effects. This contrasts with studies reporting reduced whitefly infestations under diversified cropping systems and may reflect the highly mobile nature of whiteflies and their tendency to benefit from increased canopy complexity, reduced air movement

and higher humidity within intercrops [9,31]. Seasonal climatic variability in Central Kenya may have further influenced pest population dynamics and treatment performance.

The significant treatment effects on Shannon diversity indicate that ecological management practices altered the composition and evenness of natural-enemy communities rather than uniformly increasing diversity under a single treatment. Intercrop and Botanicals + Intercrop frequently recorded higher diversity in cabbage, whereas treatment rankings varied more strongly among years in garden pea, indicating that the effects of habitat diversification depended on crop structure, pest availability and seasonal conditions. Coriander likely provided nectar, pollen, shelter and alternative prey resources that supported predators and parasitoids during periods of low pest density, consistent with the natural-enemy hypothesis and evidence that crop diversification promotes beneficial arthropods through increased habitat complexity and niche availability [32]. However, the absence of consistently higher diversity under intercropping in garden pea suggests that additional factors, including prey density, crop architecture and background landscape resources, may have been equally important in structuring natural-enemy communities. The pronounced seasonal fluctuations observed across years further indicate that climatic variability and host availability influenced natural enemies alongside local management practices. Similar seasonal variation has been reported for *Aphidius colemani*, whose populations can fluctuate considerably with host density, climatic conditions and surrounding vegetation [33,34]. Likewise, hoverflies and ladybirds have been shown to respond more strongly to temporal resource availability than to individual field practices alone [35,36]. These findings suggest that ecological management influences natural enemies primarily by modifying habitat quality and resource availability rather than by directly increasing beneficial arthropod abundance.

The treatment comparisons should be interpreted within the scope of the experimental design. The control received neither botanical applications nor coriander intercropping, and the experiment did not include a conventional insecticide or farmer-practice treatment. The results therefore show the relative responses of pests and natural enemies to the evaluated ecological treatments compared with an untreated system. They do not establish equivalence or superiority to commonly used pesticide programmes, nor do they demonstrate that the tested practices can replace synthetic insecticides. Direct comparisons that include locally representative farmer practices, registered insecticides, crop yield, application costs and operational feasibility are required before broader recommendations can be made.

5. Conclusions

No single EPM practice consistently outperformed all others across pests, seasons and response variables. However, the combined Botanicals + Intercrop treatment provided the most consistent improvements across multiple objectives, including reductions in pest damage and maintenance of natural-enemy diversity. Intercrop alone frequently supported higher natural-enemy diversity and in some cases reduced pest pressure, whereas Botanicals alone showed stronger effects against selected pest groups, particularly aphids and cutworms. These findings suggest that combining habitat diversification with botanical applications is likely to be most beneficial where farmers seek simultaneous improvements in pest management, soil quality and productivity rather than control of a single pest species. Under resource limitations, companion cropping alone may provide a lower-input alternative for supporting ecosystem services and biological regulation. The findings support the use of EPM as a component of sustainable vegetable production in smallholder systems in Central Kenya. However, further research should compare these practices with conventional farmer management, evaluate implementation costs and profitability, and validate treatment performance across multiple agroecological zones and climatic conditions.

6. Limitations of the Study

Differences observed between the cabbage and garden pea phases should not be attributed solely to crop identity because cabbage was grown exclusively during the long rains and garden pea during the short rains. Seasonal rainfall, temperature and moisture conditions may therefore have contributed to differences in pest pressure and natural-enemy responses between the two phases. The results provide evidence of treatment performance within each crop-season phase, but the present design does not permit independent estimation of crop and rainfall-season effects. The study period further experienced substantial interannual climatic variability, including marked differences in rainfall distribution and intensity among seasons, which likely influenced pest immigration, natural-enemy activity, crop growth and the persistence of botanical residues. Consequently, treatment performance should be interpreted within the context of the prevailing environmental conditions during each season.

A second limitation is the absence of conventional insecticide and farmer-practice controls. The untreated control permitted assessment of differences attributable to botanicals, coriander intercropping and their combination, but did not permit direct comparison with commonly used pesticide-based management. The findings should therefore not be interpreted as evidence that the tested EPM practices provide equivalent pest control or can replace conventional insecticides. Similarly, the study did not evaluate treatment costs, labour requirements, profitability, yield protection efficiency or farmer acceptability and therefore cannot quantify the agronomic or economic advantages of the tested practices relative to conventional management.

The study was conducted at a single long-term experimental site in Kangari, Murang'a County, and the results may therefore reflect site-specific interactions among soils, climate, surrounding vegetation and local pest communities. In addition, complete garden pea observations were unavailable for the year 2023 following crop establishment challenges, reducing the temporal continuity of the legume phase. Consequently, caution is required when extrapolating the findings to other agroecological zones, production systems or climatic regions without additional multi-location validation studies.

Author Contributions: P.N.M.: Conceptualization, Methodology, Data Curation, Formal analysis, Validation, Writing—Original Draft Preparation; M.K.: Conceptualization, Methodology, Data Curation, Validation, Writing—Review and Editing, Project administration; M.M.-M.: Supervision; F.M.: Investigation, Methodology, Data Curation, Formal analysis, Validation, Visualization, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Biovision Foundation for Ecological Development (Grant No. 1040), the Coop Sustainability Fund (Grant No. 1040), the Liechtenstein Development Service (LED) (Grant No. 1040), and the Swiss Agency for Development and Cooperation (SDC) (Grant No. 1040).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analysed during the study have been presented in the article.

Acknowledgments: The authors wish to acknowledge the financial support from the Biovision Foundation for Ecological Development, Coop Sustainability Fund, the Liechtenstein Development Service (LED), and the Swiss Agency for Development and Cooperation (SDC). They also wish to thank the management of Mwarano Primary School for offering the trial site. We are grateful to James Karanja for managing the trial site and data collection.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

The following abbreviations are used in this manuscript:

AUDPC	Area Under the Disease Progress Curve
DBM	Diamondback Moth (<i>Plutella xylostella</i>)
EPM	Ecological Pest Management
FAO	Food and Agriculture Organization of the United Nations
FiBL	Research Institute of Organic Agriculture
icipe	International Centre of Insect Physiology and Ecology
LR	Long Rain Season
MoALD	Ministry of Agriculture and Livestock Development
RCBD	Randomized Complete Block Design
SDC	Swiss Agency for Development and Cooperation
SE	Standard Error
SR	Short Rain Season
SysCom	Farming Systems Comparison Trial

Appendix A

Table A1. Mean absolute abundance and cumulative abundance pressure of cabbage pests under different EPM treatments.

Season	Treatment	Aphid		Cutworm		DBM	
		Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC
LR2020	Control	2.2 $\pm$ 0.15	128.0	0.3 $\pm$ 0.33	0.5	1.5 $\pm$ 0.15	68.5
	Botanicals	1.7 $\pm$ 0.17	65.0	0.8 $\pm$ 0.17	4.0	1.0 $\pm$ 0.16	36.5
	Intercrop	1.3 $\pm$ 0.13	59.0	0.3 $\pm$ 0.33	0.5	0.9 $\pm$ 0.14	31.0
	Botanicals + Intercrop	1.1 $\pm$ 0.16	47.5	1.0 $\pm$ na	na	0.7 $\pm$ 0.16	20.0
LR2021	Control	2.2 $\pm$ 0.26	45.5	1.0 $\pm$ na	na	1.0 $\pm$ 0.32	3.5
	Botanicals	1.9 $\pm$ 0.17	31.5	1.3 $\pm$ 0.16	9.0	1.0 $\pm$ 0.22	6.0
	Intercrop	2.4 $\pm$ 0.35	38.0	1.2 $\pm$ 0.2	4.5	1.4 $\pm$ 0.26	10.0
	Botanicals + Intercrop	1.6 $\pm$ 0.19	25.0	0.6 $\pm$ 0.24	2.5	1.2 $\pm$ 0.58	5.0
LR2022	Control	2.1 $\pm$ 0.16	74.0	0.8 $\pm$ 0.17	4.5	1.2 $\pm$ 0.31	19.0
	Botanicals	2.3 $\pm$ 0.25	43.5	1.1 $\pm$ 0.14	16.0	1.1 $\pm$ 0.28	13.5
	Intercrop	1.7 $\pm$ 0.17	52.5	0.9 $\pm$ 0.2	7.0	1.6 $\pm$ 0.41	15.0
	Botanicals + Intercrop	1.8 $\pm$ 0.17	42.5	1.6 $\pm$ 0.65	12.5	0.9 $\pm$ 0.23	12.0
LR2023	Control	1.9 $\pm$ 0.19	32.5	1.0 $\pm$ 0.26	5.5	2.2 $\pm$ 0.37	11.0
	Botanicals	2.3 $\pm$ 0.25	15.5	0.9 $\pm$ 0.2	7.0	1.7 $\pm$ 0.33	3.0
	Intercrop	1.7 $\pm$ 0.25	22.0	0.5 $\pm$ 0.29	1.5	1.8 $\pm$ 0.63	5.5
	Botanicals + Intercrop	2.3 $\pm$ 0.22	25.0	1.0 $\pm$ 0	2.0	1.2 $\pm$ 0.31	6.0
LR2024	Control	2.0 $\pm$ 0.11	69.0	0.7 $\pm$ 0.24	7.0	na	na
	Botanicals	2.1 $\pm$ 0.21	62.0	0.6 $\pm$ 0.17	13.0	1.0 $\pm$ 0	1.0
	Intercrop	1.6 $\pm$ 0.25	32.0	0.3 $\pm$ 0.13	10.0	2.0 $\pm$ 0	2.0
	Botanicals + Intercrop	2.3 $\pm$ 0.11	88.0	0.6 $\pm$ 0.19	6.5	na	na
LR2025	Control	1.5 $\pm$ 0.18	17.0	1.0 $\pm$ 0.32	4.5	1.0 $\pm$ na	na
	Botanicals	2.2 $\pm$ 0.27	22.5	1.0 $\pm$ 0	7.0	1.7 $\pm$ 0.67	3.0
	Intercrop	1.7 $\pm$ 0.19	17.5	0.8 $\pm$ 0.25	5.5	na	na
	Botanicals + Intercrop	1.8 $\pm$ 0.31	12.0	0.6 $\pm$ 0.24	2.5	na	na

na = standard error or AUDPC could not be estimated because insufficient observations were available for that treatment–season combination.

Table A2. Factorial analysis of the effects of botanical applications, companion cropping and their interaction on the overall (pooled across LR2020–LR2025) AUDPC of cabbage pest abundance.

Pest	Control	Botanicals	Intercrop	Botanicals + Intercrop	Botanicals F	<i>p</i>	Intercrop F	<i>p</i>	Bot × Int F	<i>p</i>
Aphid	61.0	40.0	36.8	40.0	1.629	0.221	2.992	0.104	2.992	0.104
Cutworm	4.3	9.3	4.8	4.4	5.536	0.035 *	4.665	0.050 *	7.614	0.016 *
DBM	22.4	10.5	11.7	7.6	3.219	0.101	2.308	0.158	0.704	0.419

* Significant at $\alpha = 0.05$.**Table A3.** Seasonal mean damage severity scores (1–5 scale) and cumulative damage intensity (AUDPC) for major cabbage pests under different EPM treatments.

Season	Treatment	Aphid		Cutworm		Dbm	
		Mean ± SE	AUDPC	Mean ± SE	AUDPC	Mean ± SE	AUDPC
LR2020	Control	2.2 ± 0.15	123.5	5.0 ± 0	10.0	2.0 ± 0.15	91.5
	Botanicals	2.1 ± 0.17	82.0	2.8 ± 0.7	13.5	1.7 ± 0.14	63.5
	Intercrop	2.0 ± 0.14	89.5	1.7 ± 0.33	3.5	1.8 ± 0.14	66.5
	Botanicals + Intercrop	2.0 ± 0.12	83.5	1.0 ± na	na	1.9 ± 0.17	58.0
LR2021	Control	2.7 ± 0.27	60.5	2.0 ± na	na	2.6 ± 0.6	11.0
	Botanicals	2.9 ± 0.34	47.5	3.6 ± 0.6	25.5	2.6 ± 0.48	15.5
	Intercrop	3.2 ± 0.37	50.5	2.6 ± 0.6	9.5	3.1 ± 0.48	22.5
	Botanicals + Intercrop	2.2 ± 0.26	33.5	3.0 ± 0.84	12.0	2.6 ± 0.6	11.0
LR2022	Control	2.4 ± 0.22	83.5	2.5 ± 0.81	11.5	2.7 ± 0.32	42.0
	Botanicals	2.2 ± 0.27	38.5	3.3 ± 0.43	47.0	1.9 ± 0.24	24.0
	Intercrop	2.2 ± 0.2	65.0	3.1 ± 0.54	23.0	2.3 ± 0.36	23.5
	Botanicals + Intercrop	2.0 ± 0.2	47.5	2.3 ± 0.62	14.5	2.2 ± 0.24	31.0
LR2023	Control	3.1 ± 0.35	52.5	2.3 ± 0.84	11.0	3.0 ± 0.63	16.5
	Botanicals	3.1 ± 0.44	20.5	3.0 ± 0.65	26.0	3.3 ± 1.2	5.5
	Intercrop	2.6 ± 0.31	37.5	4.8 ± 0.25	14.0	4.0 ± 0.71	11.5
	Botanicals + Intercrop	2.6 ± 0.34	29.0	1.0 ± 0	2.0	3.0 ± 0.63	15.0
LR2024	Control	2.3 ± 0.17	78.5	2.8 ± 0.58	30.0	na	na
	Botanicals	2.3 ± 0.14	65.0	2.3 ± 0.37	52.0	2.0 ± 0	2.0
	Intercrop	2.1 ± 0.16	45.5	2.7 ± 0.33	77.5	3.0 ± 1.0	3.0
	Botanicals + Intercrop	2.1 ± 0.16	81.5	2.2 ± 0.51	23.0	na	na
LR2025	Control	1.0 ± 0	11.0	1.0 ± 0	4.0	1.0 ± na	na
	Botanicals	1.0 ± 0	9.0	1.5 ± 0.5	11.0	1.0 ± 0	2.0
	Intercrop	1.0 ± 0	10.0	2.4 ± 0.62	17.5	na	na
	Botanicals + Intercrop	1.0 ± 0	7.0	2.6 ± 0.98	10.0	na	na

na = standard error or AUDPC could not be estimated because insufficient observations were available for that treatment–season combination.

Table A4. Factorial effects of botanical applications, companion cropping and their interaction on the overall (pooled across LR2020–LR2025) AUDPC of pest damage in cabbage.

Pest	Control	Botanicals	Intercrop	Bot + Int	Botanicals F	<i>p</i>	Intercrop F	<i>p</i>	Bot × Int F	<i>p</i>
Aphid	68.3	43.8	49.7	47.0	8.720	0.010 *	2.778	0.116	5.632	0.031 *
Cutworm	12.4	29.2	24.2	10.3	0.078	0.784	0.501	0.491	9.265	0.009 *
DBM	32.2	18.8	22.4	20.7	4.036	0.072	1.093	0.320	2.201	0.168

* Significant at $\alpha = 0.05$.**Table A5.** Mean absolute abundance and cumulative abundance pressure of garden pea pests under different EPM treatments.

Season	Treatment	Aphid		Cutworm		Whitefly	
		Mean ± SE	AUDPC	Mean ± SE	AUDPC	Mean ± SE	AUDPC
SR2020	Control	2.5 ± 0.39	58.0	0.8 ± 0.31	6.0	2.3 ± 0.33	4.5
	Botanicals	1.3 ± 0.25	23.5	0.4 ± 0.22	3.5	2.0 ± 0	2.0
	Intercrop	2.0 ± 0.18	59.0	1.3 ± 0.88	2.0	2.5 ± 0.5	2.5
	Botanicals + Intercrop	1.5 ± 0.26	25.0	1.5 ± 0.34	7.5	3.0 ± 0	3.0

Table A5. *Cont.*

Season	Treatment	Aphid		Cutworm		Whitefly	
		Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC
SR2021	Control	2.2 $\pm$ 0.27	84.0	0.8 $\pm$ 0.21	12	2.8 $\pm$ 0.2	11.0
	Botanicals	2.9 $\pm$ 0.43	80.5	0.5 $\pm$ 0.16	8.5	3.5 $\pm$ 1.19	9.5
	Intercrop	2.6 $\pm$ 0.30	102.0	1.6 $\pm$ 0.6	6.0	2.7 $\pm$ 0.29	16.5
	Botanicals + Intercrop	2.5 $\pm$ 0.41	61.5	1.6 $\pm$ 0.19	18.0	3.0 $\pm$ 0	18.0
SR2022	Control	1.7 $\pm$ 0.16	42.0	0.6 $\pm$ 0.2	8.0	3.0 $\pm$ 0	3.0
	Botanicals	2.1 $\pm$ 0.19	40.0	0.4 $\pm$ 0.15	7.5	2.0 $\pm$ 0	2.0
	Intercrop	1.8 $\pm$ 0.17	34.0	1.3 $\pm$ 0.56	6.0	2.5 $\pm$ 0.29	7.5
	Botanicals + Intercrop	2.0 $\pm$ 0.21	35.0	1.4 $\pm$ 0.32	10.0	3.0 $\pm$ 0	9.0
SR2024	Control	1.8 $\pm$ 0.17	44.0	1.1 $\pm$ 0.25	15.5	3.0 $\pm$ 0	3.0
	Botanicals	2.1 $\pm$ 0.18	41.0	0.5 $\pm$ 0.16	9.5	2.0 $\pm$ 0	2.0
	Intercrop	2.1 $\pm$ 0.12	77.0	1.3 $\pm$ 0.41	8.0	2.5 $\pm$ 0.29	7.5
	Botanicals + Intercrop	2.0 $\pm$ 0.21	38.0	1.5 $\pm$ 0.22	18.5	3.0 $\pm$ 0	9.0
SR2025	Control	2.0 $\pm$ 0.16	62.0	0 $\pm$ 0	0	2.3 $\pm$ 0.48	6.5
	Botanicals	1.6 $\pm$ 0.15	35.5	0.8 $\pm$ 0.25	2.0	1.3 $\pm$ 0.25	3.5
	Intercrop	1.8 $\pm$ 0.14	54.0	0.8 $\pm$ 0.25	2.5	1.3 $\pm$ 0.33	2.5
	Botanicals + Intercrop	2.0 $\pm$ 0.21	40.5	0.8 $\pm$ 0.25	2.0	2.0 $\pm$ 0.19	14.0

Note: Garden pea data for 2023 are not presented due to crop failure during this season, which prevented collection of sufficient pest abundance data and reliable estimation of seasonal pest pressure.

Table A6. Factorial effects of botanical applications, companion cropping and their interaction on the overall (pooled across LR2020–LR2025) AUDPC of garden pea pest abundance.

Pest	Control	Botanicals	Intercrop	Bot + Int	Botanicals F	<i>p</i>	Intercrop F	<i>p</i>	Bot $\times$ Int F	<i>p</i>
Aphid	60.3	50.2	73.3	43.6	17.926	0.001 *	0.463	0.506	4.315	0.055
Cutworm	8.9	6.6	5.1	12.3	6.277	0.024 *	0.954	0.344	23.846	<0.001 *
Whitefly	6.5	4.8	8.8	11.8	0.402	0.535	22.837	<0.001 *	5.811	0.029 *

* Significant at $\alpha = 0.05$.

Table A7. Seasonal mean damage severity scores (1–5 scale) and cumulative damage intensity (AUDPC) for major garden pea pests under different EPM treatments.

Season	Treatment	Aphid		Cutworm		Whitefly	
		Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC	Mean $\pm$ SE	AUDPC
SR2020	Control	2.0 $\pm$ 0.23	44.5	3.4 $\pm$ 0.65	22.0	1.7 $\pm$ 0.33	3.5
	Botanicals	2.2 $\pm$ 0.22	38.0	4.0 $\pm$ 0.52	35.0	2.0 $\pm$ 1.0	2.0
	Intercrop	1.8 $\pm$ 0.18	53.5	5.0 $\pm$ 0	10.0	4.0 $\pm$ 0	4.0
	Botanicals + Intercrop	1.9 $\pm$ 0.3	29.5	3.8 $\pm$ 0.54	19.5	4.0 $\pm$ 0	4.0
SR2021	Control	1.0 $\pm$ 0	38.0	3.3 $\pm$ 0.47	47.0	1.6	6.0
	Botanicals	1.0 $\pm$ 0	28.0	3.8 $\pm$ 0.38	70.0	2.5	7.0
	Intercrop	1.0 $\pm$ 0	40.0	3.4 $\pm$ 0.98	14.0	3.9	23.0
	Botanicals + Intercrop	1.0 $\pm$ 0	24.0	3.8 $\pm$ 0.41	42.0	3.6	21.0
SR2022	Control	1.9 $\pm$ 0.17	44.5	3.5 $\pm$ 0.50	44.0	2.0 $\pm$ 0	2.0
	Botanicals	2.6 $\pm$ 0.23	49.0	4.0 $\pm$ 0.36	75.0	3.0 $\pm$ 0	3.0
	Intercrop	1.6 $\pm$ 0.17	30.0	4.0 $\pm$ 0.68	21.0	4.0 $\pm$ 0	12.0
	Botanicals + Intercrop	1.9 $\pm$ 0.2	33.0	4.3 $\pm$ 0.37	30.0	4.0 $\pm$ 0	12.0
SR2024	Control	1.0 $\pm$ 0	25.0	3.3 $\pm$ 0.43	47.0	1.0 $\pm$ 0	1.0
	Botanicals	1.0 $\pm$ 0	20.0	3.9 $\pm$ 0.36	78.0	1.0 $\pm$ 0	1.0
	Intercrop	1.0 $\pm$ 0	37.0	2.6 $\pm$ 0.71	18.0	1.0 $\pm$ 0	3.0
	Botanicals + Intercrop	1.0 $\pm$ 0	19.0	3.4 $\pm$ 0.4	40.5	1.0 $\pm$ 0	3.0
SR2025	Control	1.0 $\pm$ 0	31.0	4.3 $\pm$ 0.67	9.0	1.0 $\pm$ 0	3.0
	Botanicals	1.2 $\pm$ 0.17	26.0	4.0 $\pm$ 0.58	11.0	1.0 $\pm$ 0	3.0
	Intercrop	1.0 $\pm$ 0	30.0	4.3 $\pm$ 0.75	12.0	1.0 $\pm$ 0	2.0
	Botanicals + Intercrop	1.0 $\pm$ 0	21.0	3.8 $\pm$ 0.75	11.0	1.0 $\pm$ 0	7.0

Note: Garden pea crop failure in 2023 prevented collection of sufficient damage assessment data and reliable estimation of cumulative pest damage intensity; consequently, that season was excluded from the analysis.

Table A8. Factorial effects of botanical applications, companion cropping and their interaction on the overall (pooled across LR2020–LR2025) AUDPC of garden pea pest damage.

Pest	Control	Botanicals	Intercrop	Bot + Int	Botanicals F	<i>p</i>	Intercrop F	<i>p</i>	Bot × Int F	<i>p</i>
Aphid	36.0	31.5	39.3	25.1	13.676	0.002 *	0.394	0.540	3.668	0.075
Cutworm	36.0	56.3	14.8	31.5	17.943	0.001 *	27.733	<0.001 *	0.176	0.681
Whitefly	2.9	2.5	5.5	6.3	0.064	0.804	15.107	0.001 *	0.573	0.461

* Significant at $\alpha = 0.05$.**Table A9.** Shannon diversity of key natural enemies in cabbage–garden pea rotational systems.

Year	Treatment	Cabbage		Garden Pea	
		Mean Shannon	SE	Mean Shannon	SE
2020	Control	1.40	0.11	1.05	0.06
	Botanicals	0.99	0.22	0.42	0.12
	Intercrop	1.62	0.09	0.77	0.22
	Botanicals + Intercrop	1.47	0.12	1.02	0.20
2021	Control	1.04	0.14	1.18	0.12
	Botanicals	1.06	0.14	0.99	0.14
	Intercrop	1.39	0.11	0.50	0.17
	Intercrop + Botanicals	1.30	0.11	1.08	0.15
2022	Control	1.03	0.02	1.12	0.07
	Botanicals	1.29	0.01	0.34	0.20
	Intercrop	1.52	0.07	0.33	0.19
	Intercrop + Botanicals	1.50	0.05	0.59	0.22
2023	Control	0.35	0.35	na	na
	Botanicals	0.82	0.08	na	na
	Intercrop	1.00	0.35	na	na
	Intercrop + Botanicals	1.23	0.14	na	na
2024	Control	1.19	0.07	1.12	0.07
	Botanicals	1.14	0.07	0.44	0.26
	Intercrop	1.09	0.17	0.33	0.19
	Intercrop + Botanicals	1.25	0.13	0.59	0.22
2025	Control	0.43	0.19	0.78	0.31
	Botanicals	0.25	0.20	0.81	0.09
	Intercrop	0.92	0.12	1.56	0.10
	Intercrop + Botanicals	0.91	0.12	1.55	0.02

na = Garden pea Shannon diversity values were not calculated for 2023 because crop failure during this resulted in incomplete natural enemy abundance data, making reliable estimation of the Shannon diversity index impossible.

Table A10. Shannon ANOVA for key natural enemies in cabbage–garden pea rotational systems.

Crop	Factor	Df	Sum of Squares	Mean Sum of Squares	R ²	F Value	<i>p</i> Value
Cabbage	Treatment	3	2.14	0.71	0.143	4.85	0.004
	Residuals	87	12.78	0.15			
Garden pea	Treatment	3	4.29	1.43	0.183	7.40	0.000
	Residuals	105	20.29	0.19			

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