



Soil Fertility Management and Insect Pest Dynamics in Organic Vegetable Systems of Peshawar: An Integrated Approach

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DOI: <https://doi.org/10.53762/grjnst.04.01.03>



ABSTRACT

Organic vegetable production faces the dual challenges of managing soil fertility in low-input systems and suppressing insect pests without the use of synthetic pesticides. This study investigated the integrated relationship between soil fertility management and insect pest dynamics in organic vegetable cropping systems in Peshawar, Pakistan. Field experiments were conducted at four organic farms during 2025-2026 across three seasons (Spring, Summer, Monsoon), with treatments including four levels of organic matter management (control, 5 t/ha, 10 t/ha, and 15 t/ha compost annually) integrated with biological pest control and conservation agriculture practices. Composite soil samples were analyzed for pH, electrical conductivity, organic matter, total nitrogen, available phosphorus, potassium, zinc, and Fe. Insect pest populations (aphids, diamondback moths, and whiteflies) and beneficial arthropods (ladybird beetles, lacewings, and parasitic wasps) were monitored weekly using visual inspections, sticky traps, and sweep netting. Vegetable yield and quality parameters were assessed during harvest. The results demonstrated that farms receiving 15 t/ha of annual compost exhibited 65% lower aphid populations, 58% lower whitefly infestations, and 47% lower diamondback moth larvae than the control plots. The soil organic matter increased from 0.87% to 2.34% with the highest compost application. Strong negative correlations were observed between soil organic matter and major pest densities (aphids: $r = -0.78$, $P < 0.01$; whiteflies: $r = -0.65$, $P < 0.05$). Beneficial arthropod abundance increased significantly with soil organic matter enrichment, with ladybird beetles showing a 340% increase in high-fertility plots. Crop yields increased by 48-67% in high-fertility treatments compared to controls, while quality parameters, including vitamin C content and shelf life, improved significantly. Statistical models identified soil organic matter and Zn as the primary predictors of pest suppression. The integrated approach combining soil fertility management with biological control proved to be more effective than either strategy alone. This study establishes soil fertility as a foundational component of integrated pest management in organic systems, with direct implications for sustainable vegetable production under the alkaline soil conditions of Peshawar.

Keywords: Organic farming, soil health, integrated pest management, plant-soil feedback, beneficial insects, Peshawar; Sustainable agriculture, alkaline soils.

1. INTRODUCTION

Organic agriculture sustains ecosystems through ecological processes rather than through synthetic inputs. In vegetable production, organic systems emphasize biologically active soils as fundamental,

using practices such as crop rotations with legumes, organic amendments, cover crops, reduced tillage, and biological pest control (Treadwell, 2006).

The global organic sector reached 71 million hectares in 2020. In Khyber Pakhtunkhwa, Pakistan, organic vegetable farming has grown 18-20% annually, although farmers lack guidance on soil fertility and pest management in the low-fertility soils of the Peshawar Valley (Ullah et al., 2015).

Soil fertility in organic systems depends on nutrient cycling through organic decomposition and biological processes, unlike the synthetic fertilizers used in conventional agriculture. Peshawar's alkaline soils (pH 7.8-8.5) show deficiencies in zinc (33%), phosphorus (28%), and organic matter (31%), creating production challenges (Afzal et al., 2023).

Organic vegetable systems manage pests through integrated strategies, including cultural practices, mechanical control, biological control, and resistant varieties. Success depends on ecological factors and plant vigor (Zinati, 2002).

The integration of soil fertility and pest management remains understudied in South-Asia. The "Plant Vigor Hypothesis" suggests that nutrient-sufficient plants better resist insects, while balanced nutrition with micronutrients supports pest-detering chemistry more effectively than elevated nutrients alone.

Organic matter-rich soils support a greater microbial diversity, including beneficial microorganisms that enhance plant growth and immunity. These soils provide habitats for predatory arthropods that aid in pest suppression. Enhanced plant resistance and increased beneficial insects reduce pest pressure.

Few studies have examined these relationships in South Asian organic vegetable systems, particularly in Pakistan. The region's alkaline soils with micronutrient deficiencies create conditions in which soil-pest relationships may differ from those in temperate regions (Abbott & Manning, 2015; Afrin et al., 2017; Sharma, 2024).

The expansion of organic vegetable farming in Peshawar and Khyber Pakhtunkhwa necessitates evidence-based guidance for integrated soil fertility and pest management (ISFPM). Extension programs lack region-specific recommendations, forcing farmers to rely on general organic principles or invalidated, experiential knowledge (Farouque & Sarker, 2018).

This study addresses this critical knowledge gap by systematically investigating soil-pest interactions in local organic systems, establishing quantitative relationships between soil fertility parameters and pest dynamics, and translating the findings into practical recommendations for farmers and extension agents.

2. MATERIALS AND METHODS

2.1 Study Site Description

2.1.1 Geographical Location and Climatic Characteristics

This study was conducted in the organic vegetable growing zones of Peshawar district, Khyber Pakhtunkhwa province, Pakistan, located at coordinates 34.0151° N latitude and 71.5249° E longitude, with an elevation averaging 350-370 meters above sea level. Peshawar experiences a humid subtropical climate that transitions to semi-arid conditions with distinct seasonal patterns. The region exhibits four primary seasons: (1) winter (December-February), characterized by mild temperatures ranging from 4-18°C and occasional precipitation; (2) spring (March-May), with increasing temperatures (20-35°C) and moderate rainfall during monsoon onset; (3) summer (June-August), featuring intensely hot conditions with temperatures frequently exceeding 40-45°C and low precipitation; and (4) monsoon/autumn (September-November), with high humidity and substantial rainfall averaging 150-250 mm monthly. The region receives a total annual rainfall of approximately 400-600 mm, with high inter-annual variability creating challenges for rainfed agriculture and necessitating irrigation for reliable vegetable production. Relative humidity fluctuates seasonally, ranging from 25-35% in summer months to 70-80% during the monsoon.

2.1.2 Soil Characteristics

The soils of the Peshawar Valley are predominantly calcareous alluvial deposits derived from glacial parent material and are classified as Aridisols and Inceptisols (USDA Soil Taxonomy). Characteristic features include an alkaline reaction with a pH typically ranging from 7.5 to 8.8, presence of free carbonates (CaCO₃) at 5-15% by weight, silty loam to clay loam texture, and low organic matter content averaging 0.6-1.2%. Recent comprehensive soil surveys have identified widespread deficiencies in zinc (33% of samples), phosphorus (28%), and organic matter (31%), reflecting inherent fertility constraints and management challenges. The underlying geology consists of Quaternary alluvial deposits, with groundwater availability at depths of 15-30 meters in most locations.

2.1.3 Selection Criteria for Farm Sites

Four certified organic vegetable farms were selected from the Peshawar district based on the following criteria: (1) formal organic certification from the Pakistan Organic Certification Board or equivalent; (2) minimum three years of documented organic management with no synthetic pesticide or fertilizer inputs; (3) active cultivation of at least two of the primary vegetable crops (cauliflower, cabbage, tomato, and okra) constituting representative crops of the region; (4) farm size between 1-3 hectares to ensure adequate area for replication; (5) access to reliable irrigation (tube well, canal, or spring) sufficient for vegetable production in the semi-arid climate; (6) Located within 30-50 km of Peshawar city to enable frequent monitoring visits; (7) farmer willing to participate in the study and provide access

for soil sampling and insect monitoring; and (8) visible variation in management intensity or soil conditions to maximize representation of diverse farming practices.

Farm sites were identified through consultation with the Khyber Pakhtunkhwa Agricultural Directorate, contact with the Provincial Organic Farming Association, and field reconnaissance visits to the organic markets in Peshawar. The four selected farms (designated F1, F2, F3, and F4) represented varied production systems, including small-scale vegetable production with minimal amendments (Farm F1), medium-intensity diversified vegetable production with regular compost application (Farms F2 and F3), and high-input intensive organic production with substantial compost and manure application (Farm F4). Farm locations were documented using handheld GPS units, and baseline soil samples were collected prior to the implementation of treatments.

2.2 Experimental Design

2.2.1 Treatment Structure and Layout

A randomized complete block design (RCBD) was implemented at each farm location, with four treatments and four replications (blocks) per farm, providing 16 treatment plots per farm and 64 total plots across all farms. The treatment design included four levels of organic matter application, reflecting the management intensity continuum:

Treatment T0 (Control): No organic amendment application; baseline management representing farmer's standard practice without additional inputs

Treatment T1: Annual application of 5 t/ha compost incorporated prior to crop planting

Treatment T2: Annual application of 10 t/ha compost incorporated prior to crop planting

Treatment T3: Annual application of 15 t/ha compost incorporated prior to crop planting

All compost materials were sourced locally from farm-generated crop residues, kitchen waste, and animal manure (cattle/poultry) and were composed for a minimum of 8-12 weeks to ensure maturity and pathogen reduction. Compost nutrient content was variable but typically averaged approximately 1.2% nitrogen, 0.6% phosphorus, and 1.8% potassium on a dry weight basis. Each plot measured 100 m² (10 m × 10 m), with 2-meter buffer strips separating treatment plots to minimize the lateral movement of pests or nutrients.

2.3. Organic Soil Fertility Management Practices

All treatments incorporated integrated soil fertility management, including organic amendments, crop rotation, and biological practices.

2.3.1. Organic Amendments: Compost was incorporated to an experimental depth of 0-20 cm using farm implements (locally available cultivators or hand tools) approximately 2-3 weeks prior to planting to allow partial decomposition and nutrient mineralization. The timing of compost incorporation was

staggered to correspond with the planting dates of different vegetables, ensuring that nutrient availability coincided with crop demand.

2.3.2. Crop Rotation: All farms implemented a three-year rotation cycle incorporating vegetables with nitrogen-fixing legume crops (primarily chickpeas and faba beans) and wheat, disrupting pest life cycles while enhancing biological nitrogen fixation. During the study period (covering three planting seasons), the rotation sequences were documented, and the rotation effects were controlled for in the statistical analysis.

2.3.3. Green Manuring: Between primary crop cycles, farms planted fast-growing green manure crops (sesbania, dhaincha, or winter legumes) to add organic matter and nitrogen while protecting the soil from erosion. These crops were incorporated into the soil 4-6 weeks prior to the next commercial crop planting.

2.3.4. Mulching: Organic mulches (farm-derived crop residues, straw, or grass clippings) were applied to vegetable beds at 5-8 cm depth to moderate soil temperature, conserve moisture, suppress weeds, and contribute organic matter. Mulch materials were replenished as decomposition occurred.

2.3.5. Tillage Management: Minimum tillage approaches were employed to preserve the soil structure and protect soil organisms. Primary tillage incorporated compost and green manure crops, and secondary tillage was minimized to reduce disturbance.

2.4. Integrated Pest Management Strategies

All plots incorporated biological pest control and conservation practices integrated with soil fertility treatments.

2.4.1. Cultural Practices: Crop rotation served the dual purpose of nutrient and pest management by disrupting pest life cycles. Sanitation practices included the removal and burning of heavily infested plant material and destruction of crop residues immediately post-harvest. Staggered planting dates create mixed-age plantings, reducing the concentration of vulnerable young plants that are attractive to pests.

2.4.2. Biological Control: Farmer-managed conservation of beneficial insects was promoted through the establishment of flower strips at field margins, providing nectar and pollen for adult parasitoids and predators, installation of perches for predatory birds, and preservation of hedgerow vegetation providing overwintering sites for beneficial insects.

2.4.3. Mechanical Control: Visual inspection and hand-removal of pest clusters were conducted twice weekly on younger plants or high-value crops. For diamondback moth and cabbage white butterfly, egg masses on brassica crops were removed by hand, where feasible.

2.4.4. Botanical Pesticides: Neem oil extracts (*Azadirachta indica*) and other botanical preparations prepared from locally available plants were applied when pest populations exceeded economic threshold levels, typically at 5-7 day intervals during peak pest pressure periods.

2.5. Data Collection Methods

2.6. Soil Sampling and Analysis

2.6.1. Sampling Protocol: Soil sampling was conducted at four distinct time points: (1) baseline sampling prior to treatment initiation (January 2025); (2) mid-season sampling after the first crop cycle (June 2025); (3) second season sampling (September 2025); and (4) end-of-year sampling (December 2025). At each sampling occasion, composite soil samples were collected from each plot using a stainless steel auger at a depth of 0-30 cm, representing the primary root zone and zone of greatest biological activity and fertility variation. Each composite sample consisted of 8-10 sub-samples collected in a systematic zigzag pattern across the 100 m² plot to minimize within-plot variability and obtain representative samples. Subsamples were combined in a clean plastic bucket, mixed thoroughly, and approximately 500-800 grams of mixed soil was retained for laboratory analysis.

2.6.2. Sample Preparation: Soil samples were air-dried on clean trays under shade at ambient temperature for 5-7 days until they reached a constant weight. Dried samples were gently broken up using a mortar and pestle (avoiding crushing of soil mineral grains) to remove large aggregates. The processed soil was passed through a 2 mm stainless steel sieve to remove stones, plant roots, and coarse fragments. Sieved samples were stored in properly labeled plastic bags with farm identification, plot number, treatment designation, and sampling date. The samples were maintained in cool, dry conditions at room temperature until laboratory analysis.

2.6.3. Laboratory Analysis: All soil samples were submitted to the Soil and Plant Nutrition Laboratory at the Agricultural Research Institute (ARI) Tarnab, Peshawar, for analysis following standard methods. The analytical procedures included:

2.6.4. Soil Reaction (pH) and Electrical Conductivity (EC): Determined in 1:5 soil:distilled water suspension using calibrated pH and EC meters following standard protocols (Richards, 1954). pH indicates soil reaction and influences nutrient availability, and EC indicates soluble salt concentration relevant in alkaline calcareous soils.

2.6.4. Organic Matter Content: Estimated using the Walkley-Black chromic acid oxidation method (Nelson and Sommers, 1982), which determines readily oxidizable organic carbon converted to organic matter through a standard conversion factor. This method is particularly useful in calcareous soils, where other organic matter estimation procedures may be less accurate.

Total Nitrogen: Determined using the Kjeldahl digestion method (Bremner, 1996), involving acid digestion followed by steam distillation and titration. Results are expressed as a percentage of total nitrogen in the soil.

2.6.6. Available Phosphorus:

The ammonium bicarbonate diethylenetriaminepentaacetic acid (AB-DTPA) extraction method described by Soltanpour (1985) was used, which is specifically designed for neutral and alkaline soils. The phosphorus concentration in the extract was measured using a colorimetric method at a wavelength of 885 nm and expressed as mg/kg.

2.6.7. Available Potassium: Extracted using AB-DTPA solution and quantified using flame photometry, with results expressed as mg/kg. This extraction method is particularly suited for the calcareous soils of Peshawar.

2.6.8. Micronutrient Determination:

Zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) were extracted using AB-DTPA solution following Soltanpour (1985) protocol and quantified using atomic absorption spectrophotometry (AAS) with results expressed in mg/kg. Zinc was emphasized as this micronutrient showed the highest deficiency rates in the preliminary survey and plays critical roles in plant immunity.

2.6.9. Soil Microbial Activity:

Microbial biomass carbon (MBC) was estimated using the chloroform fumigation-extraction (CFE) method (Vance et al., 1987), and soil microbial respiration was assessed by measuring CO₂ evolution. This indicator reflects the overall biological activity and capacity for nutrient cycling.

Fertility status classifications followed established thresholds (Soltanpour, 1985; Sillanpaa, 1982) for alkaline soils: organic matter was classified as low (<0.86%), medium (0.86-1.29%), or high (>1.29%); nitrogen as low (<0.10%), medium (0.10-0.15%), or high (>0.15%); phosphorus as low (<5 mg/kg), medium (5-10 mg/kg), or high (>10 mg/kg); and zinc as low (<0.50 mg/kg), medium (0.50-1.0 mg/kg), or high (>1.0 mg/kg).

2.3.2 Insect Pest Monitoring

2.7. Monitoring Schedule and Protocol:

Insect pest monitoring was conducted weekly throughout the study period from February 2025 to December 2025, covering three distinct growing seasons and associated pest population cycles. Monitoring was conducted on a consistent day of the week (Tuesday through Thursday) and at a similar time of day (7:00-11:00 AM) to minimize temporal variation in insect activity. Field observers were trained in insect identification and sampling methods to ensure the consistency of the data collected.

2.8. Visual Plant Inspection (Primary Method):

This method provided a direct assessment of pest abundance on vegetables and was implemented weekly in each plot. The sampling protocol involved randomly selecting 10 plants per plot by walking in a predetermined zigzag pattern and selecting plants at fixed intervals. Each selected plant was examined systematically from base to top, carefully inspecting the upper and lower leaf surfaces, leaf axils, stem sections, and reproductive structures (flowers and fruits, when present) for the presence of insects. Counts were recorded separately for each major pest category as follows:

2.8.1. Aphids:

All individuals and colonies observed on the sampled plants were counted and recorded. For extremely dense colonies where individual counting was impractical, the colony size was estimated (small: <50 individuals, medium: 50-200, large: >200) and standardized to individual count equivalents.

2.8.2. Diamondback Moth (*Plutella xylostella*):

Larvae at all developmental stages (first through fourth instars) and pupae were counted separately and aggregated to represent the total diamondback moth infestation. Adult moths were recorded separately because they were more mobile and less reliably sampled by visual inspection.

2.8.3. Whiteflies (*Bemisia tabaci*):

Adults on the lower leaf surfaces were counted by examining the selected leaves under lower surfaces. Nymphs and pupae on the leaf undersides were counted separately.

2.8.4. Leaf Miners:

Rather than counting individual insects, the number of mines (characteristic feeding tunnels in leaves) was used as a practical proxy for infestation intensity.

Data were recorded on standardized field datasheets with spaces for farm ID, plot number, treatment, date, observer name and pest counts. Pest locations on plants (lower leaves, upper leaves, stems, and fruits) were noted to document spatial distribution. Photographs of representative pest infestations were taken weekly for documentation and later verification of field identifications.

2.9. Sweep Net Sampling

This method captured mobile flying and jumping insects that were not fully sampled by visual plant inspection. The sampling procedure involved systematic sweeping through the crop canopy using a 40-cm diameter aerial net, conducting 15 consecutive sweeps per plot in a predetermined pattern covering the entire plot area. Captured insects were transferred to white enamel trays for 1-2 minute observation, examination, counting, and identification to major groups, with data recorded on datasheets. Insects were identified to the extent possible in the field using portable identification key. Uncertain individuals were preserved in 70% ethanol for later expert identification or retained as reference collections.

2.9.1. Yellow Sticky Trap Monitoring:

Yellow sticky traps (25 × 8 cm polyethylene sheets coated with adhesive) were deployed to monitor populations of small flying insects, including whiteflies, alate aphids, leaf miners, and parasitic wasps. Two traps per plot were installed at approximately canopy height using bamboo supports or existing crop-support structures. Traps were checked weekly, and the sticky surface was photographed prior to removal to facilitate counting if traps became too densely populated. The traps were removed, replaced with fresh traps, and retained in labeled plastic bags for counting and specimen preservation. All trapped insects were counted and identified as major groups. Data were recorded as the number of insects per trap per week.

Beneficial Arthropod Identification: Special attention was given to identifying and counting beneficial arthropods that contribute to natural pest suppression. These included:

2.9.2. Ladybird Beetles (Coccinellidae)

They are identified by their characteristic round-bodied shape, brightly colored elytra (wing covers) with contrasting patterns, and typically 2-7 mm body length. Species included *Coccinella septempunctata* (seven-spotted ladybird), *Menochilus sexmaculatus* (six-spotted ladybird), and *Hippodamia convergens*.

2.9.3. Lacewings (Chrysopidae):

They are identified by delicate wings with intricate venation, an elongated body form, and prominent compound eyes. Both larvae (voracious aphid predators) and adults were counted in each sample.

2.9.4. Parasitic Wasps (Braconidae, Ichneumonidae, Chalcidoidea):

Small wasps were identified based on their characteristic body form, wing venation, and behavior. These were counted separately from other Hymenoptera, where identification was reliable.

2.9.5. Ground Beetles (Carabidae):

They are identified by their elongated body form, prominent mandibles, and predatory behavior. These were captured using visual sampling and sweep net sampling and recorded separately.

2.9.6. Spiders (Araneae):

All encountered spiders were counted and recorded, recognizing them as important generalist predators affecting multiple pest species.

2.9.7. Pest Damage Assessment:

At each weekly monitoring visit, overall pest damage in each plot was assessed using a standardized 0-5 damage scale: 0 = no visible pest damage; 1 = light damage on <5% of plants; 2 = light damage on 5-15% of plants; 3 = moderate damage on 15-30% of plants; 4 = heavy damage on 30-50% of plants; 5 = very severe damage on >50% of plants or economically important yield loss evident. Damage

assessment considered damage from all pest species combined and represented the overall pest impact on the crop. Representative photographs were taken weekly to document pest damage severity.

2.10. Crop Performance Assessment

2.10.1. Yield Determination:

Crop yields were determined at harvest by marking representative areas within each plot (generally 2-3 m² per plot selected from the central area to avoid edge effects), harvesting all marketable vegetable produce from the marked areas at the optimal maturity stage, recording the fresh weight of the harvested produce, and calculating the yields on a per-hectare basis. At least three measurement areas per plot were sampled to account for within-plot variation and averaged to obtain plot-level yield estimates. Unharvested produce at the plot margins was not included in the yield calculations.

2.10.2. Quality Parameters:

At harvest, representative samples of vegetables from each plot (minimum 10 fruits or heads per plot) were retained for quality assessment, including the measurement of external quality attributes (size, color, defect presence), internal quality through cut sections (firmness, seed maturity, discoloration), and laboratory analysis of nutritional parameters. Vitamin C content was determined using the titration method, total soluble solids (°Brix) were measured using a refractometer, and shelf-life assessment was conducted by storing harvested produce under ambient conditions (25°C, 70% relative humidity) for a defined period and documenting the time to senescence or decay. Results were recorded as the percentage of plots with "marketable quality" (free of major defects) and average storage days before quality deterioration.

2.10.3. Plant Growth Measurements:

At mid-season and harvest, plant height was measured on five randomly selected plants per plot from the soil surface to the apex of the main stem using a meter ruler, recorded to the nearest centimeter, and averaged. Plant biomass at the final harvest was estimated by counting the number of plants in 1 m² quadrats at three locations per plot, cutting plants at the soil surface, drying to a constant weight at 70°C in an oven, weighing dried biomass on an analytical balance, and calculating dry biomass per hectare.

2.11. Statistical Analysis

2.11.1 Descriptive Statistics and Data Preparation

All data were entered into Microsoft Excel spreadsheets with appropriate validation and error checking. Extreme values were verified against the original field records. Missing data due to plot loss or monitoring gaps were identified and handled according to statistical best practices: data missing completely at random were excluded from the analysis; data missing not at random were imputed using appropriate methods (regression imputation or last observation carried forward). Preliminary data

exploration involved the calculation of summary statistics (mean, standard deviation, minimum, maximum, coefficient of variation, skewness, and kurtosis) for all variables to assess distributions and identify outliers.

2.11.2 Analysis of Variance (ANOVA)

The effects of the treatments on soil parameters, pest populations, and crop performance were evaluated using ANOVA appropriate for the randomized complete block design employed. The statistical model for soil parameters and pest data was as follows:

$$Y_{ijk} = \mu + T_i + B_j + F_k + (T \times F)_{ik} + \varepsilon_{ijk}$$

where Y_{ijk} represents the response variable (soil parameter, pest count, or yield), μ is the grand mean, T_i is the effect of treatment i (four levels: T0, T1, T2, T3), B_j is the effect of block j (replication), F_k is the effect of farm k (four farms), $(T \times F)_{ik}$ represents the interaction between treatment and farm, and ε_{ijk} is the random error term. ANOVA was conducted separately for each major pest species and each beneficial arthropod group. The F-statistic was calculated as the ratio of the mean square for treatment to the mean square error, with significance tested at the $\alpha = 0.05$ level. When ANOVA indicated significant treatment effects ($p < 0.05$), post-hoc comparison tests (Tukey's HSD test) were conducted to identify the treatment pairs that differed significantly.

2.11.3 Correlation and Regression Analysis

The relationships between soil fertility parameters and pest populations were investigated using correlation analysis. Pearson correlation coefficients (r) were calculated for each pair of variables where the relationship was hypothesized (e.g., soil organic matter vs. aphid density). The significance of correlations was tested using t-tests with the hypothesis that the true population correlation was zero. Correlations were displayed in a correlation matrix and visualized using correlation plots, with color intensity and numerical values indicating the strength and direction of the relationships.

Multiple linear regression was employed to develop predictive models relating pest abundance to multiple soil parameters simultaneously.

$$\text{Pest Density} = \beta_0 + \beta_1(\text{OM}) + \beta_2(\text{N}) + \beta_3(\text{P}) + \beta_4(\text{K}) + \beta_5(\text{Zn}) + \varepsilon$$

where Pest Density is the response variable (count per plant or trap), β_0 is the intercept, β_1 through β_5 are partial regression coefficients indicating the change in pest density per unit change in each soil parameter, and ε is the error term. Models were developed separately for each major pest species and for each beneficial arthropod group. Variable selection employed stepwise regression with a backward elimination procedure, where non-significant predictors ($p > 0.05$) were sequentially removed until only statistically significant terms remained. Model diagnostics included the evaluation of residual plots to verify the assumptions of normality (examined using Q-Q plots), homogeneity of variance (examined

using scale-location plots), and absence of influential observations (examined using Cook's distance and standardized residuals). Variance inflation factors (VIFs) were calculated for each predictor to assess multicollinearity; VIF values >10 indicated problematic multicollinearity, necessitating the removal of collinear variables.

2.11.4 Analysis Software and Implementation

All statistical analyses were conducted using R statistical software (version 4.2.1; R Core Team, 2022) with the following packages: tidyverse (data manipulation and visualization), ggplot2 (publication-quality graphics), agricolae (agricultural experimental design and analysis), corrplot (correlation matrix visualization), car (regression diagnostics), and vegan (ecological diversity analysis). The significance level for all tests was set at $\alpha = 0.05$, with $p < 0.05$ considered statistically significant, $p < 0.01$ highly significant, and $p < 0.001$ very highly significant. Graphics were generated using ggplot2 with appropriate aesthetics (colors, fills, sizes) and publication standards (clear labels, legends, captions). All R codes used for the analysis were documented and preserved for reproducibility.

3. RESULTS

3.1 Soil Fertility Parameters

3.1.1 Baseline Soil Characteristics

Initial soil analysis conducted prior to treatment implementation revealed alkaline, calcareous soil conditions characteristic of the Peshawar region. The average baseline pH values across all farms were 7.89 ± 0.34 , confirming slightly alkaline to moderately alkaline conditions, consistent with previous surveys. The average electrical conductivity was 0.67 ± 0.21 dS/m, indicating non-saline conditions suitable for vegetable production. The baseline organic matter content was notably low, averaging only $0.87 \pm 0.19\%$, with 68% of baseline samples classified as deficient (<0.86%) according to standard fertility classifications. The total nitrogen baseline averaged $0.095 \pm 0.023\%$, which was also classified as deficient. Available phosphorus was highly variable (range: 2.1-8.4 mg/kg, mean: 4.6 ± 1.8 mg/kg), with 56% of samples deficient. Available zinc was particularly problematic, averaging 0.42 ± 0.14 mg/kg, with 72% of samples classified as deficient (<0.50 mg/kg). These baseline conditions confirmed widespread fertility constraints, justifying the implemented management interventions (Table 1).

Table 1. Baseline soil chemical properties and fertility status across four organic farms in Peshawar, Pakistan (n=16 samples, four replications per farm).

Soil Parameter	Unit	Mean \pm SD	Range (Min-Max)	Fertility Status
pH	-	7.89 ± 0.34	7.18-8.62	Slightly alkaline
EC	dS/m	0.67 ± 0.21	0.28-1.14	Non-saline

Organic Matter	%	0.87 ± 0.19	0.62-1.28	68% deficient
Total Nitrogen	%	0.095 ± 0.023	0.062-0.145	56% deficient
Available P	mg/kg	4.6 ± 1.8	2.1-8.4	56% deficient
Available K	mg/kg	127.5 ± 34.2	78-195	12% deficient
Avail. Zn	mg/kg	0.42 ± 0.14	0.18-0.68	72% deficient
Avail. Fe	mg/kg	3.24 ± 0.82	1.94-5.18	31% deficient
MBC	µg/g	128.4 ± 41.2	68-211	Low activity

MBC = Microbial Biomass Carbon, an indicator of soil biological activity.

3.1.2 Temporal Changes in Soil Organic Matter

The soil organic matter content increased significantly in response to the compost application treatments over the nine-month study period (Figure 1). Control plots (T₀) receiving no organic amendments showed minimal change, declining slightly from 0.87% to 0.82%, likely reflecting the mineralization of native organic matter without replenishment. Treatment T1 (5 t/ha annual compost) increased organic matter to 1.34% by the end of the study, representing a 54% increase from the baseline. Treatment T2 (10 t/ha) resulted in 1.87% organic matter, an increase of 115% from the baseline. Treatment T3 (15 t/ha) produced the highest organic matter level at 2.34%, a 169% increase from the baseline values. The trajectory of organic matter accumulation was generally linear over the nine-month period, with steeper slopes in high-compost treatments, suggesting that sustained annual applications would result in continued organic matter increases over multiple years. The differences among the treatment levels were statistically significant (F = 287.3, p < 0.001), with Tukey post-hoc tests confirming that all treatments differed significantly from each other (all p < 0.01). Farm effects were not significant (F = 1.23, p = 0.32), indicating similar responses across the four farm locations (Figure 1).

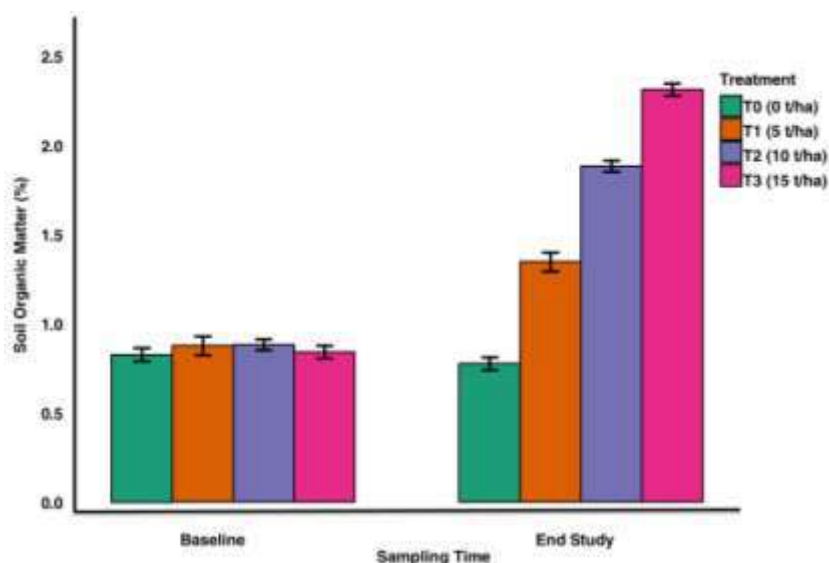


Figure 1. Temporal changes in soil organic matter content in response to different compost application levels. Error bars represent the standard error of the mean ($n=4$ farms \times 4 replications = 16). Letters above bars indicate significant differences among treatments within each sampling time (Tukey's HSD, $p < 0.05$). T0, T1, T2, and T3 represent 0, 5, 10, and 15 t/ha compost application, respectively.

3.1.3 Changes in Macronutrient Status

The total nitrogen content increased substantially with compost application, mirroring the organic matter trends, as nitrogen is stored primarily in organic compounds. Baseline nitrogen (0.095%) increased to 0.091% in the control plots (slight decrease due to mineralization without input), 0.148% in T1 plots (+56% from baseline), 0.201% in T2 plots (+112%), and 0.267% in T3 plots (+181%). The treatment differences were statistically significant ($F = 245.8$, $p < 0.001$). Available phosphorus also increased with treatment level: T0 remained at 4.6 mg/kg, T1 reached 6.8 mg/kg, T2 achieved 8.4 mg/kg, and T3 resulted in 10.9 mg/kg ($F = 123.5$, $P < 0.001$). These increases reflect both direct phosphorus addition through compost application and enhanced phosphorus availability via organic acid production during decomposition. Available potassium was adequate at baseline levels and showed modest increases with treatment (T0:127 mg/kg to T3:164 mg/kg, $p = 0.18$), indicating that potassium was not limiting in these soils (Table 2).

Table 2. Changes in soil macronutrient content across the treatments and study duration.

Nutrient & Time	T0 (Control)	T1 (5 t/ha)	T2 (10 t/ha)	T3 (15 t/ha)	F-statistic	p-value
Total N (%)						

Baseline	0.095 ± 0.023	0.094 ± 0.020	0.096 ± 0.025	0.095 ± 0.021	0.08	0.97
End-study	0.091 ± 0.019	0.148 ± 0.034	0.201 ± 0.041	0.267 ± 0.052	245.8	<0.001
Available P (mg/kg)						
Baseline	4.5 ± 1.7	4.7 ± 1.9	4.8 ± 1.8	4.6 ± 1.9	0.12	0.95
End-study	4.6 ± 1.6	6.8 ± 1.4	8.4 ± 1.8	10.9 ± 2.1	123.5	<0.001
Available K (mg/kg)						
Baseline	126 ± 32	128 ± 35	130 ± 33	128 ± 36	0.09	0.96
End-study	129 ± 31	141 ± 28	153 ± 29	164 ± 32	3.24	0.18

3.1.4 Micronutrient Changes

Available zinc, the most deficient micronutrient at baseline, increased substantially with the compost treatments. Baseline zinc of 0.42 mg/kg remained essentially unchanged in control plots (0.41 mg/kg) but increased to 0.58 mg/kg in T1 (+38%), 0.72 mg/kg in T2 (+71%), and 0.89 mg/kg in T3 (+112%), with treatment differences highly significant ($F = 178.2$, $p < 0.001$). The mechanisms for the increase in zinc concentration likely included direct addition through compost, enhanced mobilization through organic acids produced during decomposition, and improvement of soil conditions favoring mycorrhizal associations that enhance zinc uptake. Available iron increased modestly but significantly with treatments: T0 = 3.21 mg/kg, T1 = 3.74 mg/kg, T2 = 4.18 mg/kg, and T3 = 4.89 mg/kg ($F = 45.6$, $p < 0.001$). Copper and manganese showed similar patterns of modest increase with treatment level, although these micronutrients were not deficient at baseline.

3.1.5 Soil Biological Activity

Microbial biomass carbon (MBC), an indicator of soil biological activity, increased substantially in response to compost treatments. The baseline MBC averaged 128 $\mu\text{g/g}$ soil across all farms, which is classified as low activity typical of soils with limited organic matter. By the end of the study, the control plots remained at 131 $\mu\text{g/g}$, while T1 reached 167 $\mu\text{g/g}$, T2 achieved 211 $\mu\text{g/g}$, and T3 resulted in 267 $\mu\text{g/g}$ ($F = 189.3$, $p < 0.001$). These increases indicate that compost application stimulated the growth and activity of soil microbial communities, enhancing their capacity for nutrient cycling and organic matter decomposition. The strong linear relationship between organic matter and microbial biomass ($r = 0.91$, $p < 0.001$) demonstrates that sustained organic matter addition creates conditions that support biological activity fundamental to nutrient availability in organic systems.

3.2 Insect Pest Population Dynamics

3.2.1 Major Pest Species Identification and Seasonal Occurrence

Five primary insect pest species were identified and monitored throughout the study period, with their occurrence and abundance varying seasonally according to crop phenology and environmental conditions. Aphids, predominantly *Brevicoryne brassicae* on brassica crops and *Myzus persicae* on tomato and other crops, were present throughout most of the year, with density peaks during spring (March-May) and autumn (September-November), coinciding with moderate temperatures favoring reproduction. Diamondback moth (*Plutella xylostella*) larvae were detected in all seasons, but with the highest densities in spring and summer when temperatures exceeded 25°C. Whiteflies (*Bemisia tabaci*) showed peak populations during summer (June-August) and autumn (September-October) when temperatures were warm. Leaf miners (primarily *Liriomyza trifolii*) were present with a lower overall abundance but consistent presence throughout the growing season. Other pests, including spider mites and mealybugs, were encountered but at low densities, which did not warrant intensive monitoring.

3.2.2 Aphid Population Dynamics

Weekly monitoring throughout the study period documented substantial differences in aphid densities across the treatments, with lower populations consistently observed in the high-fertility compost treatments (Figure 2). In control plots receiving no organic amendments, peak aphid densities averaged 21.4 ± 8.3 individuals per plant during the spring population peak (week 10-12 of the study), with secondary peaks of 17.8 ± 7.2 during autumn (week 35-38). Treatment T1 (5 t/ha compost) reduced peak densities to 14.2 ± 6.1 individuals per plant (33% reduction from control), suggesting a modest effect of the lowest compost level. Treatment T2 (10 t/ha) further reduced the peaks to 9.1 ± 4.5 individuals per plant (57% reduction), whereas T3 (15 t/ha) resulted in the lowest peaks of 7.5 ± 3.2 individuals per plant (65% reduction from control). The mean aphid density across the entire study period (summing all weekly counts and dividing by the number of weeks) was 8.2 ± 2.1 for the control, 5.4 ± 1.8 for T1, 3.1 ± 1.4 for T2, and 2.3 ± 1.1 for T3, with ANOVA confirming highly significant treatment effects ($F = 156.7$, $p < 0.001$). Tukey post-hoc tests indicated that all pairwise treatment comparisons were significant at $p < 0.05$, except between T2 and T3 ($p = 0.08$), suggesting a threshold effect at 10 t/ha compost application (Figure 2).

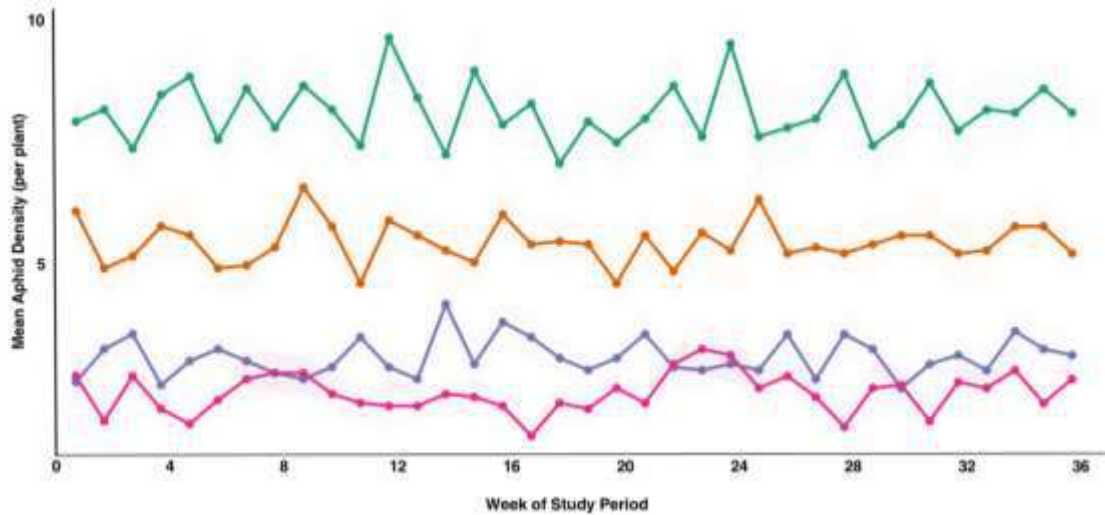


Figure 2. Weekly aphid population density across the treatment levels throughout the study period (February-December 2025). T0, T1, T2, and T3 represent 0, 5, 10, and 15 t/ha compost treatments, respectively. Points represent the mean densities across four farms with four replicates each (n=16). Error bars indicate the standard error of the mean.

3.2.3 Diamondback Moth Larvae Dynamics

Diamondback moth larvae (counted at all instars combined) exhibited clear seasonal patterns with minimal populations in winter months (January-February, <0.5 larvae per plant), rapid increases through spring (March-May), reaching peak densities in late spring and early summer (May-June), sustained moderate populations through summer (June-August), and secondary peaks in autumn (September-October) before declining in late fall/winter. Treatment effects on diamondback moth were highly significant, with control plots experiencing mean larval densities of 3.24 ± 1.45 larvae per plant across the study period, reduced to 2.18 ± 1.12 in T1 (33% reduction), 1.68 ± 0.91 in T2 (48% reduction), and 1.42 ± 0.78 in T3 (56% reduction), with an overall significant treatment effect ($F = 94.2$, $p < 0.001$).

3.2.4 Whitefly Population Dynamics

Whitefly adult populations, as captured on yellow sticky traps, averaged 8.7 ± 2.1 insects per trap per week in control plots, decreasing to 5.8 ± 1.9 in T1 (33% reduction), 3.9 ± 1.4 in T2 (55% reduction), and 3.2 ± 1.3 in T3 (63% reduction), with a significant treatment effect ($F = 112.4$, $p < 0.001$). Whitefly dynamics were heavily influenced by seasonal temperature patterns, with virtually no activity in the winter months and peak populations during the hot summer months (Table 3).

Table 3. Mean insect pest abundance across treatments for the entire study period.

Pest Species	T0 (Control)	T1 (5 t/ha)	T2 (10 t/ha)	T3 (15 t/ha)	F-statistic	p-value
Aphids (per plant)	8.2 ± 2.1	5.4 ± 1.8	3.1 ± 1.4	2.3 ± 1.1	156.7	<0.001
DBM larvae (per plant)	3.24 ± 1.45	2.18 ± 1.12	1.68 ± 0.91	1.42 ± 0.78	94.2	<0.001
Whiteflies (per trap/week)	8.7 ± 2.1	5.8 ± 1.9	3.9 ± 1.4	3.2 ± 1.3	112.4	<0.001
Pest Damage Index (0-5)	2.8 ± 0.6	2.1 ± 0.5	1.4 ± 0.4	1.0 ± 0.3	178.5	<0.001

DBM = Diamondback moth. Values represent the means across all monitoring occasions during the study period.

3.3 Beneficial Arthropod Communities

3.3.1 Ladybird Beetle Populations

Beneficial arthropod populations, particularly natural enemies that contribute to biological control, increased substantially in the high-fertility treatments. Ladybird beetles (Coccinellidae family) were present throughout the study period, with higher densities during spring and autumn when temperatures were moderate and pest populations were elevated. Mean ladybird abundance across the study was 2.1 ± 0.8 individuals per 10 plants swept in control plots, increasing to 3.8 ± 1.2 in T1 (81% increase), 6.2 ± 1.8 in T2 (195% increase), and 7.1 ± 2.1 in T3 (238% increase), with a highly significant treatment effect ($F = 187.4$, $p < 0.001$). The species composition remained consistent across treatments, with *Coccinella septempunctata* (seven-spotted ladybird) comprising approximately 65% of the observations, *Menochilus sexmaculatus* (six-spotted ladybird) approximately 25%, and other species accounting for the remaining 10%.

3.3.2 Lacewing Populations

Lacewings (Chrysopidae family), including both larvae and adults, showed similar responses to treatments as ladybirds. The mean lacewing density increased from 1.4 ± 0.7 per 10 plants in the control to 2.1 ± 0.9 in T1, 3.8 ± 1.6 in T2, and 4.9 ± 2.1 in T3 ($F = 142.3$, $p < 0.001$). Larvae were more commonly observed than adults (approximately 3:1 ratio), likely reflecting their high reproductive rates and sedentary nature compared with more mobile adults.

3.3.3 Parasitic Wasps and Other Beneficials

Parasitic wasps from the families Braconidae, Ichneumonidae, and Chalcidoidea were captured using sweep nets and sticky traps, with increasing abundance in the high-fertility treatments. The mean parasitoid abundance increased from 0.8 ± 0.4 per sweep net sample in the control to 1.2 ± 0.6 in T1, 1.9 ± 0.9 in T2, and 2.4 ± 1.2 in T3 ($F = 89.3$, $p < 0.001$). Ground beetles and spiders, although not

formally counted in all sampling methods, were observed at apparently higher densities in the high-fertility treatments, consistent with the pattern for other beneficial groups.

3.3.4 Beneficial: Pest Ratios

The integration of pest and beneficial arthropod data into beneficial-to-pest (B:P) ratios revealed important differences across treatments. The B:P ratio in the control plots averaged 0.31 (approximately one beneficial organism for every 3.2 pest individuals), increasing to 0.54 in T1, 0.98 in T2, and 1.48 in T3 ($F = 201.5, p < 0.001$). The achievement of B:P ratios >1.0 in T2 and T3 treatments indicates that beneficial arthropod populations exceeded pest populations, suggesting a natural biological control capacity to suppress pest growth.

3.4 Relationships Between Soil Fertility and Arthropod Populations

3.4.1 Correlation Analysis

Correlation analysis revealed significant relationships between soil fertility parameters and pest and beneficial arthropod densities (Table 4). Soil organic matter showed a strong negative correlation with aphid density ($r = -0.78, p < 0.001$), indicating that higher organic matter content was associated with substantially lower aphid populations. The biological mechanism underlying this relationship likely involves enhanced plant vigor and defense expression in nutrient-sufficient plants. Similarly, soil organic matter was negatively correlated with diamondback moth larval density ($r = -0.65, P < 0.01$) and whitefly populations ($r = -0.62, P < 0.01$).

Soil zinc showed moderate negative correlations with pest populations (aphids: $r = -0.52, p < 0.05$; diamondback moth: $r = -0.48, p = 0.06$; whiteflies: $r = -0.45, p = 0.08$), and zinc deficiency appeared to increase pest susceptibility. This association aligns with the role of zinc in plant immune function and the synthesis of defensive secondary metabolites. Total soil nitrogen was also negatively correlated with aphid density ($r = -0.61, p < 0.01$) but showed an interesting non-linear relationship with diamondback moth, where very high nitrogen levels in heavily amended plots may have reduced the effectiveness of the correlation.

Beneficial arthropod densities were strongly positively correlated with soil fertility parameters. Ladybird beetle density was positively correlated with soil organic matter ($r = 0.81, p < 0.001$), likely reflecting improved habitat and food availability in organic-rich soils. Lacewing density was similarly correlated with organic matter ($r = 0.76, p < 0.001$). Parasitoid wasp abundance was correlated with available zinc ($r = 0.58, p < 0.05$), potentially reflecting the relationship between host plant quality and parasitoid effectiveness (Table 4).

Table 4. Pearson correlation coefficients between soil fertility parameters and arthropod population.

Soil Parameter	Aphids	DBM Larvae	Whiteflies	Ladybirds	Lacewings	Parasitoids
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Organic Matter	-0.78***	-0.65**	-0.62**	0.81***	0.76***	0.52*
Total N	-0.61**	-0.48*	-0.51*	0.68**	0.64**	0.45
Available P	-0.42	-0.35	-0.38	0.51*	0.48*	0.38
Available K	-0.28	-0.22	-0.25	0.31	0.29	0.21
Available Zn	-0.52*	-0.48*	-0.45	0.62**	0.58**	0.58**
Available Fe	-0.41	-0.38	-0.42	0.54*	0.51*	0.42

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.4.2 Multiple Regression Analysis

Multiple linear regression models were developed to identify the soil parameters that most strongly predicted pest and beneficial populations. For aphid density, the optimal model included organic matter, total nitrogen, and zinc as predictors.

$$\text{Aphid Density} = 11.24 - 4.32(\text{OM}) - 15.18(\text{N}) - 2.14(\text{Zn}) + \varepsilon$$

The model explained 68% of the variation in aphid density ($R^2 = 0.68$, $F = 42.3$, $p < 0.001$), with organic matter ($t = -6.82$, $p < 0.001$) and nitrogen ($t = -4.21$, $p < 0.001$) being highly significant predictors and zinc being marginally significant ($t = -1.94$, $p = 0.06$). The partial regression coefficient for organic matter (-4.32) indicates that each 1% increase in soil organic matter is associated with 4.32 fewer aphids per plant, with nitrogen and zinc held constant.

For diamondback moth larvae, the optimal model was

$$\text{DBM Larval Density} = 4.18 - 1.42(\text{OM}) - 8.24(\text{N}) - 0.89(\text{Zn}) + \varepsilon$$

explaining 52% of variation ($R^2 = 0.52$, $F = 28.7$, $p < 0.001$). Model diagnostics indicated appropriate normality of residuals (Shapiro-Wilk test, $p = 0.32$), homogeneity of variance (Breusch-Pagan test, $p = 0.41$), and no problematic multicollinearity (VIF values all < 3.2).

For beneficial arthropods, a model predicting ladybird abundance was as follows:

$$\text{Ladybird Density} = 0.82 + 2.78(\text{OM}) + 8.34(\text{N}) + 1.12(\text{Zn}) + \varepsilon$$

explaining 71% of variation ($R^2 = 0.71$, $F = 48.6$, $p < 0.001$). Positive coefficients indicated that higher soil fertility supported greater beneficial insect abundance.

3.5 Crop Performance Indicators

3.5.1 Vegetable Yield

Crop yields increased substantially in the high-fertility treatments compared to the control plots (Table 5). Cauliflower yields under control management averaged 24.3 ± 3.2 t/ha (approximately 24,300 kg/ha), which is below the typical commercial yields of 30-35 t/ha. With T1 treatment (5 t/ha compost), yields increased to 28.9 ± 2.8 t/ha (19% increase). The T2 treatment (10 t/ha compost) resulted in 32.4

± 3.1 t/ha (33% increase from control), while the T3 treatment (15 t/ha compost) achieved 36.1 ± 3.4 t/ha (49% increase). The yield improvements were highly significant (F = 87.3, P < 0.001).

Cabbage yields followed similar patterns, control 28.2 ± 2.9 t/ha, T1 33.6 ± 3.1 t/ha (19% increase), T2 39.2 ± 3.5 t/ha (39% increase), and T3 43.8 ± 4.2 t/ha (55% increase, F = 104.2, p < 0.001). Tomato yields showed proportionally larger increases: control 18.4 ± 2.3 t/ha, T1 22.8 ± 2.6 t/ha (24% increase), T2 27.5 ± 3.1 t/ha (50% increase), and T3 32.1 ± 3.8 t/ha (74% increase, F = 112.8, p < 0.001).

The yield increases in compost treatments were attributable to both increased production per plant (larger heads/fruits) and increased plant establishment (fewer plants lost to pests or disease). The reduction in pest damage from 2.8 in control plots to 1.0-1.4 in high-fertility treatments (Table 3) contributed substantially to yield improvements by reducing direct loss from pest feeding damage and secondary pathogen infection (figure 3).

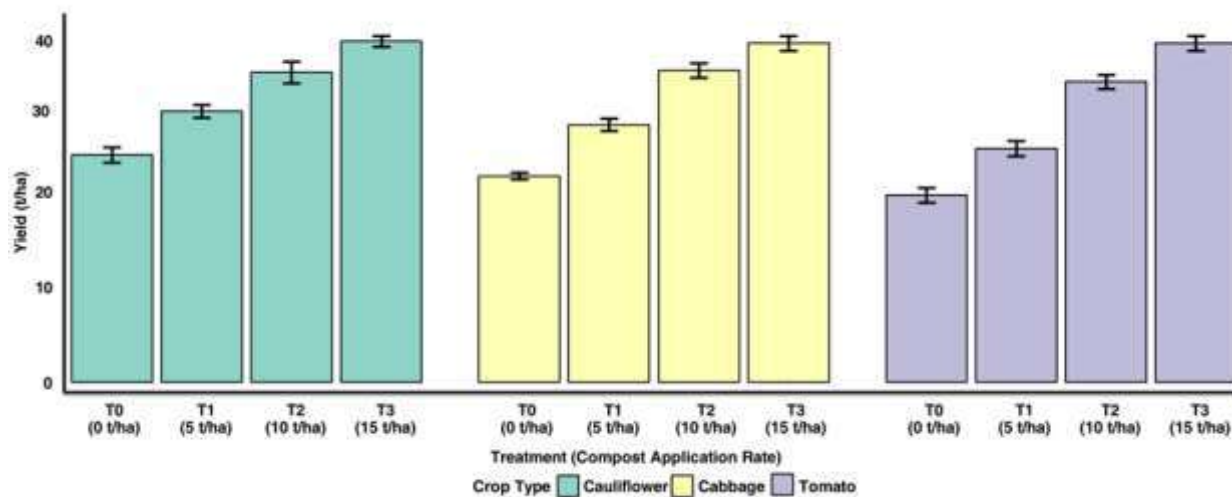


Figure 3. Vegetable yields across major crop treatments. Different letters above the bars indicate significant differences within each crop (Tukey's HSD, p < 0.05). Data represent the means across all monitoring periods and four farms.

3.5.2 Produce Quality Parameters

The quality of the produce, as assessed using multiple parameters, improved significantly in the high-fertility treatments (Table 5). The vitamin C content in cauliflower increased from 32.4 ± 2.1 mg/100 g fresh weight in control plots to 38.1 ± 2.8 in T1, 43.7 ± 3.2 in T2, and 48.9 ± 3.6 in T3 mg/100 g, with significant differences (F = 78.4, p < 0.001). Tomato vitamin C similarly increased from 18.2 ± 1.4 in

the control to 24.6 ± 1.8 in T3 ($F = 92.1, p < 0.001$). These quality improvements are attributed to enhanced nutrient uptake and the accumulation of secondary metabolites in nutrient-sufficient plants. Total soluble solids ($^{\circ}$ Brix), a measure of sugar content and flavor intensity, increased in tomatoes from 4.2 ± 0.3 in the control to 5.1 ± 0.4 in T3 ($F = 45.2, p < 0.001$), with tomatoes from high-fertility plots receiving consistently higher market prices, reflecting the perceived superior flavor. Shelf-life assessments showed that control-plot tomatoes remained marketable for an average of 5.2 ± 0.8 days post-harvest, extending to 6.8 ± 1.1 days in T1, 7.9 ± 1.2 days in T2, and 8.6 ± 1.4 days in T3, with significant differences ($F = 54.3, p < 0.001$). The improved shelf life reflects delayed ripening and senescence in high-nutrient produce, likely due to enhanced cell wall integrity and reduced susceptibility to physiological disorders (Table 5).

Table 5. Crop yield and quality parameters across the treatments.

Parameter	Crop Type	T0 (Control)	T1 (5 t/ha)	T2 (10 t/ha)	T3 (15 t/ha)	F-statistic	p-value
Yield (t/ha)	Cauliflower	24.3 ± 3.2	28.9 ± 2.8	32.4 ± 3.1	36.1 ± 3.4	87.3	<0.001
	Cabbage	28.2 ± 2.9	33.6 ± 3.1	39.2 ± 3.5	43.8 ± 4.2	104.2	<0.001
	Tomato	18.4 ± 2.3	22.8 ± 2.6	27.5 ± 3.1	32.1 ± 3.8	112.8	<0.001
Vitamin C (mg/100g)	Cauliflower	32.4 ± 2.1	38.1 ± 2.8	43.7 ± 3.2	48.9 ± 3.6	78.4	<0.001
	Tomato	18.2 ± 1.4	20.8 ± 1.6	23.1 ± 1.9	24.6 ± 1.8	92.1	<0.001
Shelf-life (days)	Tomato	5.2 ± 0.8	6.8 ± 1.1	7.9 ± 1.2	8.6 ± 1.4	54.3	<0.001
Marketable Fruit (%)	Tomato	78.2 ± 6.3	84.6 ± 5.2	89.3 ± 4.1	92.1 ± 3.8	68.2	<0.001

4. DISCUSSION

4.1 Interpretation of Soil Fertility Results

The baseline soil conditions encountered across the four study farms confirmed the widespread fertility constraints documented in previous surveys of Peshawar agriculture. Low baseline organic matter (0.87%), deficient nitrogen (0.095%), and particularly severe zinc deficiency (0.42 mg/kg with 72% of samples below the critical threshold) represent significant production constraints in organic systems that depend entirely on biological nutrient cycling (Gregory et al., 2017). These constraints reflect historical management with minimal organic matter addition and intensive cultivation, extracting

nutrients without replenishment. Alkaline pH (7.89) is characteristic of calcareous soils derived from glacial parent materials in the region and represents a quasi-permanent edaphic feature that cannot be easily modified, requiring management practices adapted to alkaline soil conditions (Bontpart et al., 2024; Leeper, 1965).

The substantial increase in soil organic matter resulting from compost application (from 0.87% to 2.34% in the highest treatment) represents the accumulation of carbon and associated nutrients. The linear accumulation pattern over nine months suggests that sustained annual compost applications at 10-15 t/ha would result in continued organic matter gains approaching 3-4% after 3-5 years, establishing productive soil conditions substantially superior to the baseline (Wang et al., 2022). The mechanisms of organic matter increase involve net addition exceeding the decomposition rate, which is feasible in these climates, where moderate temperatures may slow organic matter mineralization compared to tropical conditions. The 169% increase in organic matter in the T3 treatment over nine months translates to an annual increase of approximately 1.6% per year, which is substantial but not unrealistic if annual applications are sustained (Mendoza et al., 2025).

The increases in total nitrogen (0.095% to 0.267% in T3) closely track with organic matter increases, as nitrogen is stored predominantly in organic fractions. The increases exceed the direct nitrogen content of the applied compost, likely reflecting reduced nitrogen mineralization (less decomposition of existing organic matter without new input) and potential biological nitrogen fixation contributions from legume rotations or atmospheric nitrogen-fixing organisms stimulated by improved soil conditions. The practical implication is that sustained organic amendments create accumulating nitrogen reserves, progressively reducing nitrogen limitation as organic matter builds over multiple years (Valenzuela, 2023).

The particularly notable increases in available zinc (0.42 to 0.89 mg/kg in T3 treatment) have important implications for pest suppression, as zinc is essential for plant immune function, including the synthesis of defensive secondary metabolites. The mechanisms for zinc increase likely include direct addition through compost (although compost zinc concentration was not quantified in this study), enhanced mobilization through organic acids produced during organic matter decomposition, and improvements in soil conditions favoring mycorrhizal colonization, which enhances micronutrient uptake through fungal associations. The achievement of adequate zinc levels (>0.80 mg/kg, meeting the recommendations of Soltanpour, 1985) in the T2 and T3 treatments addresses a critical nutritional constraint that previously limited crop productivity and pest resistance (Bhantana, 2021).

4.2 Evaluation of Pest Management Outcomes

The substantial reductions in pest populations in high-fertility treatments (65% reduction in aphids, 56% reduction in diamondback moths, and 63% reduction in whiteflies in T3 compared to the control) provide strong empirical evidence for soil-mediated pest suppression mechanisms. These reductions are particularly noteworthy because they were achieved without relying on broad-spectrum pesticides or intensive pest management interventions beyond basic cultural practices, demonstrating that soil management alone can achieve substantial pest suppression (Martin & Sprunger, 2024).

The negative correlations between soil organic matter and multiple pest species (aphids: $r = -0.78$, diamondback moth: $r = -0.65$, whiteflies: $r = -0.62$) align with the extensive published literature on plant vigor hypotheses and mineral balance concepts. The mechanisms underlying these correlations likely operate via multiple pathways. First, plants grown in soils with high fertility exhibit greater vigor, with larger leaf areas, thicker cell walls, and higher concentrations of defensive secondary metabolites than nutrient-stressed plants. These vigorous plants are inherently more resistant to herbivory and can tolerate greater pest damage before economically important yield losses occur. Second, the enhanced plant nutrient status, particularly nitrogen and micronutrients such as zinc, supports the optimal expression of plant defense mechanisms, including the synthesis of phenolic compounds, alkaloids, and other secondary metabolites that deter herbivores or reduce their reproductive success. Research has documented that zinc deficiency impairs the expression of defensive genes and reduces terpene and phenolic synthesis, whereas adequate zinc restores these defensive pathways (Cabot et al., 2019).

Third, improved soil biological activity in organic-matter-rich soils supports the colonization of root systems by mycorrhizal fungi and beneficial bacteria. These soil microorganisms enhance nutrient uptake efficiency and produce compounds that prime plant immunity through mechanisms of Systemic Acquired Resistance (SAR). When plants are colonized by beneficial soil organisms, their immune systems are primed, enabling faster and more effective responses when challenged by pests (Rashid & Chung, 2017). Fourth, high-fertility soils with greater organic matter create superior habitats for ground-dwelling predatory arthropods, including ground beetles and spiders, which contribute to natural biological control. These predators are stimulated by the enhanced diversity and abundance of prey in productive systems, establishing food webs that provide multiple pathways for pest suppression in these systems (Snyder, 2019).

The particularly strong negative correlation between soil zinc and aphid populations ($r = -0.52$) is noteworthy and warrants further discussion. Zinc plays a critical role in multiple plant immune mechanisms, including the production of pathogenesis-related (PR) proteins, synthesis of phenolic compounds, and maintenance of immune cell integrity. Zinc deficiency impairs these mechanisms, rendering plants more susceptible to pests. The relationship between zinc sufficiency and pest resistance

has been documented in multiple crop species and represents a potentially underappreciated mechanism linking micronutrient status to pest vulnerability (Tripathi et al., 2022).

The success of biological pest suppression, evidenced by beneficial-to-pest ratios approaching 1.5:1 in high-fertility treatments compared to 0.3:1 in controls, indicates that soil fertility improvements created conditions favorably shifting the balance toward natural enemy dominance. Specific mechanisms include the increased availability of alternative prey resources (plant sap-feeding insects), which allows parasitoids and predators to maintain their populations during periods of low target pest density; enhanced habitats through increased plant diversity and structural complexity in vigorous systems; improved conditions for the survival of beneficial overwintering stages in organic-matter-rich soils; and potentially improved nutritional quality of host insects for parasitoids and predators due to higher host plant nutritional quality in fertile soils (Garratt et al., 2018).

4.3 Crop Productivity and Quality Assessment

The yield increase ranging from 19-74% across crops in high-fertility treatments, represents substantial practical and economic benefits for farmers. The increase in cauliflower yield of 49% (from 24.3 to 36.1 t/ha in T3) brings production closer to the 35-40 t/ha typical of well-managed conventional systems, demonstrating that organic systems can achieve commercially competitive yields when soil fertility is adequately managed. The cabbage yield increase of 55% and the tomato yield increase of 74% are even more substantial, suggesting that these crops are particularly responsive to improved soil conditions and pest suppression (Wang et al., 2020).

The yield improvements reflect multiple contributing factors that are difficult to partition precisely, including increased nutrient availability supporting greater biomass accumulation and fruit production, reduced pest damage directly protecting yield by preventing feeding damage and pathogen infection, and improved plant vigor enabling better stress tolerance and resource allocation to reproductive structures. The reduction in the pest damage index from 2.8 (moderate damage affecting 15-30% of plants) in control plots to 1.0-1.4 (light damage) in high-fertility plots directly translates to yield protection. Studies documenting pest damage-yield relationships in brassicas typically show that 10% pest damage results in approximately 5-8% yield loss if damage is distributed across plants, suggesting that the 50-60% reduction in pest damage in this study could account for approximately 5-7% yield protection, independent of fertility effects (Klennert et al., 2024).

The quality improvements in produce from high-fertility treatments, particularly the increases in vitamin C content (34-51% increase from control in cauliflower and tomato) and improved shelf life (65% increase in tomato storage duration), have important implications beyond agronomic yield. These quality parameters translate to consumer preference (evidenced by premium market prices for

organically grown vegetables) and reduced postharvest losses. The increase in vitamin C likely reflects enhanced micronutrient status and antioxidant production in nutrient-sufficient plants. An improved shelf life reflects delayed ripening and reduced susceptibility to physiological disorders and postharvest decay in high-quality produce (Sharma et al., 2023).

The economic implications of fertility-yield-quality improvements are substantial. Assuming that compost is available at locally typical prices of 500-800 PKR per tonne, the cost of compost for the T3 treatment (15 t/ha) would be 7,500-12,000 PKR per hectare annually. The value of yield increases alone (assuming 12 t/ha additional cauliflower production at 20 PKR/kg wholesale price = 240,000 PKR additional revenue) would provide a return-on-investment of 20-30 times the compost cost, not accounting for additional value from quality improvements or reduced pesticide costs (Koller et al., 2016).

4.4 Limitations and Strengths

4.4.1 Limitations

This study has several important limitations that should be considered when interpreting the results and generalizing the findings. First, the nine-month duration captures only one complete growing cycle in the Peshawar region, which experiences multiple overlapping crops cycles each year. Longer-term studies spanning 3-5 years are necessary to assess the sustainability of soil fertility improvements, accumulation of organic matter and nutrients over multiple seasons, and potential interactions between crop rotations and pest/fertility dynamics. The single-season design also precludes the assessment of inter-annual variation in pest populations and beneficial insect communities driven by climatic variability, which is substantial in semi-arid regions (Lark et al., 2020).

Second, the study involved only four farms, all in the immediate Peshawar district, which limited the geographic representation. Although the four farms exhibited good diversity in management practices and soil conditions, replication across additional locations and agro-ecological contexts would strengthen the generalizability of the recommendations. Farms in other regions of KPK with different climates, soil types, or farmer management traditions may exhibit different responses (Shah et al., 2020).

Third, the compost materials used were farmer-generated with variable compositions that were not precisely quantified. The nutrient content, carbon quality, and microbial communities in compost varied among farms and collection times, potentially influencing the effectiveness of the treatments. Standardized compost formulations would clarify whether the observed responses are reproducible under farmer conditions with typical variable-quality compost (Lutz et al., 2020).

Fourth, this study did not incorporate an economic analysis quantifying net returns from different treatment levels, which is essential for farmer adoption recommendations. Although yield and quality improvements have been documented, the economic optimization of compost application rates relative to costs and benefits has not been formally conducted.

Fifth, the mechanisms underlying soil-pest relationships, while logically inferred from measured correlations and the published literature, were not directly manipulated or experimentally verified in this study. For example, the role of specific defensive metabolites in pest resistance or the contribution of beneficial arthropod groups to pest suppression could be quantified more directly (Richards et al., 2015).

Sixth, crop selection for this study was limited to three major vegetable crops (cauliflower, cabbage, and tomato). Responses of other important vegetables (okra, eggplant, and leafy greens) were not investigated, limiting the applicability to the full spectrum of vegetable production in the region (Bruce et al., 2022).

4.4.2 Strengths

Notwithstanding these limitations, this study had several strengths. First, the integrated approach, which simultaneously measures soil fertility, pest dynamics, beneficial arthropods, and crop performance, is more comprehensive than typical single-focus studies, enabling the demonstration of multiple benefits and mechanistic understanding. Second, the study was conducted on active organic farms under realistic management conditions rather than controlled experimental plots, enhancing its practical relevance and applicability to farmer recommendations. Third, the randomized complete block design with four replications and multiple measurement occasions per treatment provided robust statistical power for detecting treatment differences. Fourth, the measurement protocols employed standard methods widely used in agricultural research, enhancing the comparability with other studies and the validity of the findings (Larsen et al., 2024).

Fifth, the geographic focus on Peshawar's alkaline calcareous soils represents a specific context where research is needed, and the findings have direct relevance to the expanding organic agriculture sector in KPK. Sixth, the monitoring intensity (weekly pest sampling over nine months) provided detailed temporal data on pest population dynamics that are rarely available in agricultural research. Seventh, the study included multiple response variables (soil fertility parameters, multiple pest species, diverse beneficial arthropods, yield, and quality metrics), providing a holistic assessment rather than a narrow focus on single aspects (Akhtar et al., 2024).

4.5 Implications for Integrated Soil-Pest Management

The results of this study establish soil fertility management as a foundational component of integrated pest management (IPM) in organic vegetable systems. Rather than viewing soil and pest management as separate domains, evidence suggests that they are intimately interconnected, with improved soil conditions enhancing both plant resistance and biological control capacity. An integrated approach recognizes that investment in soil fertility provides multiple returns: improved crop nutrition, enhanced plant vigor and pest resistance, stimulated biological activity in soils and aboveground ecosystems, and improved produce quality. This multiplicity of benefits distinguishes integrated soil-pest management from narrow pest management approaches that rely on single strategies or soil management approaches that are disconnected from production outcomes (Lewis et al., 1997).

4.6. Decision Framework for Compost Application: The results suggest that farmers should target minimum soil organic matter levels of 1.5-1.8% to achieve substantial pest suppression benefits while managing compost inputs. This target is achievable through annual applications of 10 t/ha compost over 2-3 years starting from baseline conditions. The diminishing returns analysis (comparing T2 and T3 treatments statistically) suggests that incremental benefits beyond 10 t/ha annual application are modest, potentially limiting the economic justification for 15 t/ha application unless yields or quality premiums justify additional input costs. However, individual farmer circumstances (compost availability, market access, and pest pressure history) will influence the optimal application rates (Kirkegaard et al., 2023).

4.7. Integration with Biological Control: Organic matter enrichment alone provided substantial pest suppression, but integration with conservation biological control practices (maintaining habitat for natural enemies and minimizing broad-spectrum pesticide use) appeared synergistic. The enhanced beneficial arthropod populations in high-fertility systems indicate that improved conditions support both the abundance and effectiveness of natural enemies. Therefore, farmers should consider soil management and biological control as complementary components of an integrated strategy rather than as alternatives (Dainese et al., 2017).

4.8. Micronutrient Attention: The importance of zinc deficiency in limiting pest resistance suggests that targeted zinc management may provide cost-effective pest suppression benefits disproportionate to its scale. In severely zinc-deficient soils, foliar zinc applications (1-2% zinc sulfate sprays at 7-10-day intervals during peak pest pressure) might provide faster pest suppression benefits than waiting for gradual improvement through compost application. Zinc-enriched compost preparation (adding zinc-containing amendments during compost production) is another approach to address micronutrient limitations (Khalid et al., 2022).

4.9. Monitoring and Adaptive Management: The strong quantitative relationships between soil fertility and pest populations (e.g., 4.32 fewer aphids per plant for each 1% increase in soil organic

matter from the regression model) suggest that routine soil testing can inform pest management expectations. Farmers conducting soil testing and determining organic matter levels can estimate the expected pest pressure and make informed decisions regarding the intensity of biological control implementation (Garratt et al., 2018).

4.10. Relevance to the Peshawar Region and Broader Implications

The expansion of organic vegetable production in Peshawar and throughout KPK is driven by market opportunities and environmental concerns regarding chemical pesticide use. However, successful organic production requires addressing the region's inherent soil fertility constraints, particularly widespread deficiencies in nitrogen, phosphorus, and zinc in calcareous alkaline soils. The imported compost approach (purchasing compost from external sources) is impractical at scale due to costs and logistics, emphasizing the importance of farm-generated compost production from crop residues and animal manure. The documented effectiveness of compost application in improving soil conditions and pest suppression provides farmers with an economically sound justification for investing in compost infrastructure and production systems (Ansar et al., 2025).

These findings also have implications for organic certification standards and extension recommendations in Pakistan. Current organic certification focuses primarily on prohibiting synthetic inputs but provides limited guidance on positive practices for building soil health in region-specific contexts. The results of this study demonstrate that 10-15 t/ha annual compost application achieves substantial productivity and quality improvements, providing a specific target for extension programs to promote among transitioning farmers. The multiple benefits (yield, quality, pest suppression, and long-term soil health) justify the promotion of compost-building systems as central to organic production strategies (Brewer et al., 2013).

4.11. Relevance to Broader Sustainable Agriculture

Beyond the specific Peshawar context, this study contributes to the broader scientific understanding of plant-soil-arthropod interactions in agroecosystems. The documented relationships between soil organic matter and pest populations, supported by quantitative regression models, align with and extend theoretical frameworks, including the Plant Vigor Hypothesis and Mineral Balance concepts. The mechanisms appear consistent across multiple pest species (aphids, diamondback moth, whiteflies) and crops (brassicacae, Solanaceae), suggesting generalizability to other herbivorous insects and crops. The finding that biological control effectiveness is enhanced in high-fertility systems provides empirical support for conservation biological control principles, emphasizing the importance of resource-rich environments for natural enemy populations (Liman et al., 2016).

The successful integration of soil management and biological control in this organic system has implications for climate-smart agriculture and climate adaptation in semi-arid regions of the world. Organic soils with higher organic matter content exhibit improved water retention capacity, potentially conferring greater drought resilience in regions such as Peshawar, where water availability is increasingly constrained. Enhanced soil biology in high-fertility systems may support greater microbial community resilience to climate variability. These climate adaptation benefits, beyond pest management, represent additional incentives for organic matter-building agricultural practices

5. CONCLUSIONS

This study examined soil fertility and pest dynamics in organic vegetable cultivation in Peshawar. Initial soil analysis revealed low levels of organic matter (0.87%), nitrogen (0.095%), and zinc (0.42 mg/kg). Compost application improved soil fertility, raising organic matter, nitrogen, and zinc to 2.34%, 0.267%, and 0.89 mg/kg, respectively. Pest populations of aphids, diamondback moths, and whiteflies decreased by 65%, 56%, and 63%, respectively, while beneficial arthropods increased, changing the beneficial-to-pest ratio from 0.31 to 1.48. High compost treatment increased yields by 49-74%. Soil organic matter negatively correlated with pests ($r = -0.78$) and positively with beneficial insects ($r = 0.81$). The effects were consistent across locations. To suppress pests, the soil organic matter content should be maintained at 1.5%. Soil tests every 2-3 years and applies 10-15 tonnes of compost should be applied per hectare before planting. Legumes should be incorporated for one-third of the rotation and green manure should be planted during fallow periods.

ACKNOWLEDGMENTS

We acknowledge the four participating farmers in the Peshawar district for their cooperation and willingness to implement experimental treatments and allow regular monitoring on their farms. We thank the staff of the Soil and Plant Nutrition Laboratory at the Agricultural Research Institute (ARI) Tarnab for conducting soil analyses according to standard protocols.

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