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RESEARCH ARTICLE

Modifying Canopy Microclimate and Plant Physiology to Suppress Pest Infestation and Enhance Yield in Bitter Gourd (*Momordica charantia* L.)

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Abstract
Bitter gourd (*Momordica charantia* L.) productivity is significantly constrained by insect pests, notably the melon fruit fly (Bactrocera cucurbitae). This study investigated the impact of canopy microclimate modification through plant density and integrated nutrient regimes on pest infestation and yield. A field experiment using a Randomized Complete Block Design with 2×3 factorial arrangement was conducted in Department of Agronomy Faculty of Agriculture Gomal University, Dera Ismail Khan, Pakistan, in 2025. Treatments included two plant densities (D1: high, D2: low) and three nutrient levels (N0: control, N1: NPK, N2: NPK + Zn + B). Results revealed that high density (D1) increased vegetative growth and leaf area index but created a humid microclimate (up to 84.0% humidity) conducive to fruit fly (48.2% infestation) and aphid colonization. In contrast, wider spacing (D2) combined with integrated nutrients (N2) optimized canopy ventilation and light penetration, significantly reducing fruit fly infestation to 18.2% and increasing marketable yield to 14.8 t/ha. D2N2 (T6) emerged as the most effective strategy, balancing physiological performance and pest suppression to maximize yield. These findings underscore the importance of joint optimization of plant density and balanced nutrition for sustainable bitter gourd production.

Keywords: *Momordica charantia* L., Melon fruit fly (Bactrocera cucurbitae), Photosynthetic rate, Integrated nutrient management, Marketable fruit yield

1. Introduction

Bitter gourd (*Momordica charantia* L.) locally known as karela, is one of the most important cucurbitaceous vegetables grown in South and Southeast Asia such as Pakistan, India, Bangladesh, China and Philippines for its nutritional and economic value. The agriculture sector in Pakistan is still playing the central role as it accounts for 23.5 % of GDP and more than 37 % of the labour force, vegetables are one of the key sub-segments of horticulture industry (Anonymous, 2025). It has high nutritional and medicinal value due to its hypoglycemic, antioxidant, anti-inflammatory compounds like charantin and momordicin which makes it an important crop for food security and traditional medicine system (Grover et al., 2004). Although it has gained

commercial interest, bitter gourd productivity is still limited due to various biotic and abiotic stresses which are most severe as a result of insect pest attack particularly by melon fruit fly, Bactrocera cucurbitae Coquillett (Sen et al., 2019).

The plant canopy constitutes the direct interaction point between a plant and the aerial environment and plays a key role in controlling the amount of light entering the crop, air flow under and around the stand, plant temperature, and relative humidity. Most cucurbit infesting insects are poikilotherms, meaning their eggs, larvae and adults are sensitive to humidity and temperature gradients inside the canopy Most cucurbit-infesting insects are poikilotherms, and their eggs, larvae, and adults are sensitive to humidity and temperature gradients within the canopy (Deguine et al., 2015; Schöneberg et al., 2022) which directly affects their oviposition behavior, larval survival, and adult activity, which directly affects their oviposition behavior, larval survival and adult activity. Additionally, canopy architecture influences plant physiology, such as stomatal conductance, transpiration, and partitioning of photosynthate into fruit, which ultimately impacts fruit quality, sugar concentrations, and yield (Liu et al., 2026). The conceptual framework for the present study on the effects of deliberate manipulation of canopy structure by practices like pruning, training, spacing, orientation and physical exclusion on both pest control and yield of bitter gourd (*Momordica charantia* L.) is interlinkage between microclimate, plant physiology and pest ecology (Mosedale et al., 2024).

The physiological basis for the crop canopy structure and pest incidence relationship has not been well understood, but the relationship itself has long been known in agronomic practice. Historical growers of vine crops, like grapes, cucubits, and legumes, have traditionally relied on trellising, staking and pruning to promote better air flow and light penetration, especially for improving fruit quality (Overview of the Vineyard Canopy Management, University of Missouri Extension) (Gogi et al., 2014). The idea of dense, poorly ventilated canopies and subsequent rises in humidity and fungus disease and insect harborage first appeared in early 20th century horticultural literature, and by the 1980s "microclimate modification via management" was formally proposed as part of integrated pest management (IPM) (Hatfield, 1982).

In the case of bitter gourd early pest-management studies led to almost exclusive emphasis on the control of melon fruit fly, and organophosphate insecticides were the most recommended ones from the 1970s through the 1990s. Chemical control was found to be inherently inefficient, however, due to B. cucurbitae larvae feeding endophytically within the fruit, so the host-plant resistance and biochemical fruit traits as alternative or complementary control measures were explored from the early 2000s onwards (Aravinthraju et al., 2024). More recently canopy density and architecture have been shown to measurably change within canopy temperature and humidity and thus influence pest colonization patterns, for example, in caneberries and blueberries, where pruning treatments were shown to produce small but consistent changes in within canopy microclimate that affected levels of Drosophila suzukii infestations. Aerial modification of crop environment by parallel installation of protective structures like agronets and shade nets has been found to decrease insect pest pressure and optimize plant physiological traits like stomatal conductance and CO_2 assimilation (Formisano et al., 2020). The aggregate of these works reflects the transition from chemical use as a pest management option to a more ecologically-sound, canopy-based cultural approach, in which this study of bitter gourd fits.

Yield loss is a significant problem in bitter gourd production in South Asia caused by fruit fly infestation, with losses ranging from 30% to as high as 100% (Evaluation of different pest management modules in bitter gourd Management of Cucurbit Fruit Flies in Bitter Gourd by Pheromone Traps). Fruit fly infestation in Pakistan has been reported as high as 55% and yield losses as high as 46% in some of the most resistant varieties (Sarwar, 2017). Conventional foliar insecticides provide moderate control and their repeated and often indiscriminate use can lead to pesticide residues, higher production costs and toxicity concerns, especially since bitter gourd fruit is often eaten fresh or juiced. Current methods involve cultivar-specific host-plant resistance screening, botanical

extracts, pheromone and bait traps and synthetic insecticides, and each has been effective to some degree and generally requires high labor inputs or is not economically viable for smallholders (Stonehouse et al., 2002). Little attention has been given to a fundamental, low cost tool that growers have at their disposal their plant canopy architecture. In other crops such as carrot, grapevine, blueberry, French bean, canopy modification has been found to influence pest/pathogen pressure and microclimate, but knowledge of how canopy modification alters pest/pathogen pressure and how it affects plant physiological mechanisms that influence yield is not well documented in the literature for bitter gourd (Kumar et al., 2026). This gap is also a big constraint in developing sustainable, chemical reduced pest management recommendation for this economically important crop.

This is a hot and under-researched topic of crop physiology, microclimatology and applied entomology in bitter gourd cultivation. The research assesses canopy based interventions as a novel approach to control pest infestation and improve yield and provides an alternative cultural management strategy that can decrease reliance on synthetic insecticides, reduce production costs and residues, and contribute to environmentally sustainable vegetable production. Beyond simply thinking about canopy modification as a pest management tool, understanding the effect of canopy modification on plant physiological traits like photosynthetic rate, stomatal conductance, and assimilate partitioning will also give mechanistic insight into the yields that could be expected from canopy modification. The results would be relevant for smallholder and commercial growers growing bitter gourd in areas where the crop is produced and would provide scientific information on microclimate mediated pest suppression of cucurbitaceous crops. The present study was therefore designed with the following specific objectives To evaluate the effect of plant density and nutrient regimes on canopy microclimate (humidity, light penetration) and plant physiological traits (photosynthesis, SPAD chlorophyll). To assess the impact of modified canopy microclimates and balanced nutrition on suppressing key insect pests, particularly melon fruit fly, aphids, and whiteflies. To quantify the response of fruit yield and yield components to variable spacing and nutrient management.To identify the optimal combination of plant density and nutrient regimes for maximum marketable yield and minimal pest damage.

2. Methodology

2.1 Place of Work and Facilities Available

This study was carried out at the Agronomic Research Area of Faculty of Agriculture, Gomal University, Dera Ismail Khan in year 2025. The experimental area falls under the agro climatic zone of semi arid with hot summer and mild winter typical of the Dera Ismail Khan region that is suitable for growing cucurbitaceous vegetable crops. The Department of Agronomy provided all the field facilities including irrigation laboratory facilities for physiological and biochemical analysis and meteorological data recording instruments for the successful conduct of the trial.

2.2 Experimental Design and Layout

The experiment was laid out in a Randomized Complete Block Design (RCBD) with a 2 × 3 factorial arrangement, replicated three times, comprising 18 experimental units (plots). Each plot measured 3.0 m × 3.6 m (10.8 m^2). Within each plot, five plants were randomly selected and tagged for all physiological, growth, and pest measurements. For destructive sampling (larval density), ten infested fruits per plot were randomly selected at each picking. Randomization was performed using a random number generator, and treatments were re-randomized within each block. The buffer distance of 0.75 m was used between adjacent plots in a block to

avoid nutrient movement in the soil matrix, overlap of irrigation and inter plot pest movement, and the distance of 1.0 m was maintained between replications. The total gross experimental field area including border rows, pathways and field bunds was around 700 to 750 m^2 in total.

2.3 Experimental Factors and Treatments

Factor A: Plant Density / Spacing (2 Levels)

D_1 (High Density / Narrow Spacing): 1.5 m × 0.6 m (creates a denser canopy microclimate)

D_2 (Low Density / Wide Spacing): 2.0 m × 0.6 m (creates an open, well-aerated canopy microclimate)

Factor B: Integrated Nutrient Regimes (3 Levels)

N_0 (Control): No fertilizer application

N_1 (Recommended NPK): Standard inorganic fertilizer dose (100 : 60 : 50 kg $N:P_2O_5:K_2O$ ha^{-1})

N_2 (Enhanced / Micronutrient Integrated): Recommended NPK + Zinc (10 kg ha^{-1}) + Boron (2 kg ha^{-1})

2.4 Treatment Combinations

Treatment Code	Plant Density	Nutrient Regime	Operational Description
T_1	D_1 (1.5 × 0.6 m)	N_0 (Control)	High plant density, no fertilizer applied
T_2	D_1 (1.5 × 0.6 m)	N_1 (Recommended NPK)	High plant density + Recommended NPK (100:60:50 kg ha^1
T_3	D_1 (1.5 × 0.6 m)	N_2 (NPK + Zn + B)	High plant density + NPK (100:60:50 kg ha^1) + Zn 10 kg ha^1 + B 2 kg ha^1
T_4	D_2 (2.0 × 0.6 m)	N_0 (Control)	Low plant density, no fertilizer applied
T_5	D_2 (2.0 × 0.6 m)	N_1 (Recommended NPK)	Recommended NPK (100:60:50 kg ha^1
T_6	D_2 (2.0 × 0.6 m)	N_2 (NPK + Zn + B)	Low plant density + NPK (100:60:50 kg ha^1) + Zn 10 kg ha^1 + B 2 kg ha^1

2.5 Crop, Cultivar, and Sowing Details

Test material was a locally recommended bitter gourd cultivar which is high yielding cultivar Faisalabad Long. The seeds were planted in the well-prepared raised bed (ridge and furrow) at a depth of 2–3 cm. Two seeds were planted per hill and thinned to one healthy seedling per hill after establishment as per spacing treatment (D1 or D2). Sowing was done at the recommended Kharif sowing time for the region and the cultural practices

such as irrigation, weeding, staking/training on trellis among the various treatments were standardized other than the imposed treatments.

2.6 Fertilizer and Nutrient Application

The experimental field was treated with the standard nutrient management practices as per the treatments. All recommended rates of phosphorus and potassium and half the recommended rate of nitrogen were applied at the time of land preparation and sowing. The other half of the nitrogen was top dressed into two equal applications, one at vegetative vine elongation stage and another when flowering and fruit-set began. The enhanced nutrient regime treatment (N2) involved the application of zinc sulphate (10 kg ha^{-1}) and borax (2 kg ha^{-1}) as basal rates along with recommended NPK. As part of the initial field preparation, the entire field was treated with well-decomposed farmyard manure (FYM) to ensure the baseline condition of organic matter without affecting the treatment factors to be evaluated. The furrow irrigation method was used for irrigation of the experimental units such that all units received the same rate of irrigation at 7 to 10 day intervals, depending on environmental temperature, soil moisture conditions, and precipitation. No synthetic chemical insecticides were sprayed during the cropping season in order to measure the natural incidence and suppression of insect pests as response variables accurately. Seed treatment was only given before sowing to avoid seed rot and seedling damping-off and no other pesticide treatments were used to influence the population dynamics of the pests.

2.7 Trellising and Training System

A uniform vertical trellising system was implemented throughout all plots to ensure that the architecture and microclimatic differences of the canopy were entirely under the control of the imposed plant density treatment (D1 vs. D2). The plants were trained systematically on an overhead trellis system that comprises bamboo/wooden poles of vertical and high tensile wire of horizontal poles, and nylon twines, all installed at the same height of 1.8 m. Growing vines vertically limited unchecked ground sprawl, imposed a consistent plant structural orientation, and enabled plant spacing to be the sole major determinant of canopy density, light interception and internal relative humidity.

2.8 Parameters/Variables to Be Studied

Vine Length (cm)

Measured with the help of Precision Commercial Measuring Tape (Model: Lufkin, USA) when at full vegetative maturity from the soil surface to the terminal apex of the main vine on randomly selected tagged plants per plot.

Leaf Area Index (LAI)

Non destructive canopy sampling was done during the peak flowering stage between 11:00 AM and 1:00 PM. Below plant canopy readings were done at three random points on each plot. AccuPAR LAI Ceptometer (Leaf Area Meter (Model: LI-3000C, LI-COR, USA).

SPAD Chlorophyll Content (SPAD Units)

Three fully expanded leaves of the upper third of the canopy per plant, in the early fruiting stage, measured using a Konica Minolta SPAD Chlorophyll Meter (Model: SPAD-502 Plus, Japan).

Net Photosynthetic Rate

Measurements of gas exchange were taken on fully expanded functional leaves during daylight hours between 09:00 AM and 11:30 AM in sunny conditions. Portable Photosynthesis System (Model: LI-6400XT, LI-COR, USA).

Canopy Relative Humidity (%)

The digital sensor was inserted within the mid canopy and microclimate measurements were made within the plant canopy at weekly intervals. Digital Thermo-Hygrometer (Made in China: Model: HTC-1).

Fruit Fly Infestation Incidence (%)

Procedure: At each harvest picking, all harvested fruits per plot were sorted into healthy and damaged categories.
Calculation Formula:
Fruit fly infestation (%) = (Number of infested fruits per plot / Total number of fruits harvested per plot) × 100

Larval Density per Fruit (No./fruit)

A sample of ten infested fruits was randomly selected per plot at each picking. Fruits were dissected longitudinally using a surgical scalpel to count internal maggots (larvae).
Calculation Formula:
Larval density (larvae $fruit^{-1}$) = Total count of larvae dissected / Total number of infested fruits dissected

Aphid Population Density (No./leaf)

Visual counts were performed weekly early in the morning on five randomly selected plants per plot, sampling upper, middle, and lower leaves.
Calculation Formula:

$$\text{Aphid Density (No./leaf)} = \frac{\text{Total Aphids Counted on Sample Leaves}}{\text{Total Number of Leaves Screened}}$$

Average Fruit Weight (g)

Marketable fruits harvested from selected plants in each plot were weighed collectively and averaged. Electronic Digital Balance (Model: Ohaus Adventurer AX224, USA).
Calculation Formula:

$$\text{Average Fruit Weight (g)} = \frac{\text{Total Weight of Marketable Fruits per Plot (g)}}{\text{Total Number of Marketable Fruits Harvested per Plot}}$$

Marketable Fruit Yield (t ha^{-1})

Total weight of undamaged, marketable fruits harvested across all pickings per plot was recorded and converted to metric tons per hectare. Digital Platform Scale & Calculations.
Calculation Formula:

$$[\text{Total marketable fruit weight per plot (kg)} / \text{Plot area (m}^2\text{)}] \times 10$$

2.9 Meteorological Data

This study was conducted over a single growing season (2025); therefore, the results reflect the specific weather conditions of that year (Figure 1). The early season was hot and dry (mean maximum temperature 39.5–41.2°C; rainfall 2.4–12.0 mm in May–June), while July–August received higher rainfall (82.5 mm and 38.2 mm, respectively). These conditions likely intensified the microclimatic contrast between dense (D1) and open (D2) canopies. Under cooler or wetter seasons, the humidity differential between spacing treatments may be less pronounced, potentially reducing the pest-suppression advantage of wider spacing. Multi-year and multi-location trials are therefore recommended to validate the robustness of D2N2 across variable climatic conditions, particularly given projected increases in temperature and rainfall variability in South Asia.

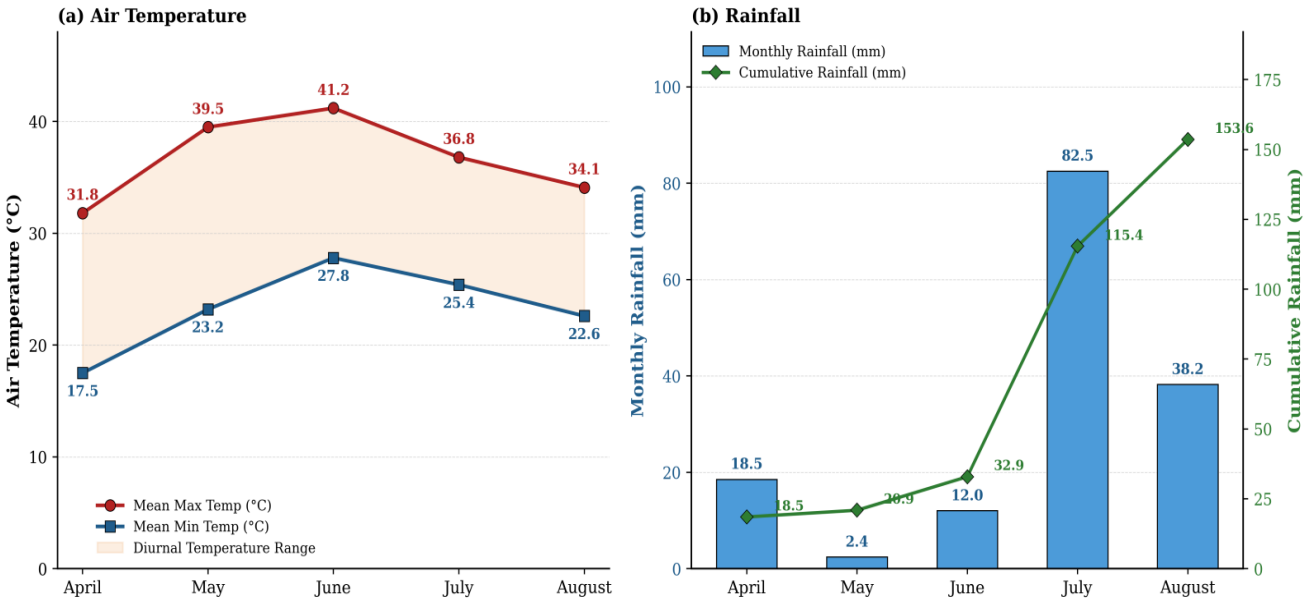


Figure 1. Meteorological conditions during the crop growing season (April–August): (a) mean maximum and minimum air temperature with shaded diurnal temperature range, and (b) monthly and cumulative rainfall.

2.10 Statistical Analysis

Data were analyzed using Analysis of Variance (ANOVA) for a two-factor factorial design in RCBD via Statistix 8.1. Means for main effects (Plant Density and Nutrient Regimes) and their interactions (A x B) were separated using the Least Significant Difference (LSD) test at a 5% probability level ($P <= 0.05$). Additionally, correlation and regression analyses were performed to determine the functional relationships between canopy microclimate, physiological traits, pest infestation levels, and fruit yield.

3. Results

3.1 Growth traits

VPlant density and integrated nutrient regimes (INRs) had a strong effect on growth parameters of vines (Figure 1). Treatment T3 (D1N2) had the longest vines (238.6 cm) while T4 (D2N0) had the shortest (152.0 cm). Similarly the maximum Leaf Area Index (LAI) was noted in T3 (D1N2, 4.65) while the lowest LAI was recorded in T4, (D2N0, 2.10). Conversely SPAD chlorophyll content followed a different trend peaking at in T6, (D2N2, 55.6) whereas the lowest value was recorded in T4, (D2N0, 34.2). vine length high density (D1) triggered shade avoidance and vertical vine elongation, while integrated nutrients (N2) promoted cell division and shoot extension. leaf Area Index denser plant populations (D1) combined with balanced nutrition (N2) maximized canopy foliage accumulation per unit area. The use of SPAD Chlorophyll open spacing (D2) allowed full light penetration and reduced the mutual shading effect, resulting in an increased nitrogen use efficiency and chloroplast development/leaf unit.

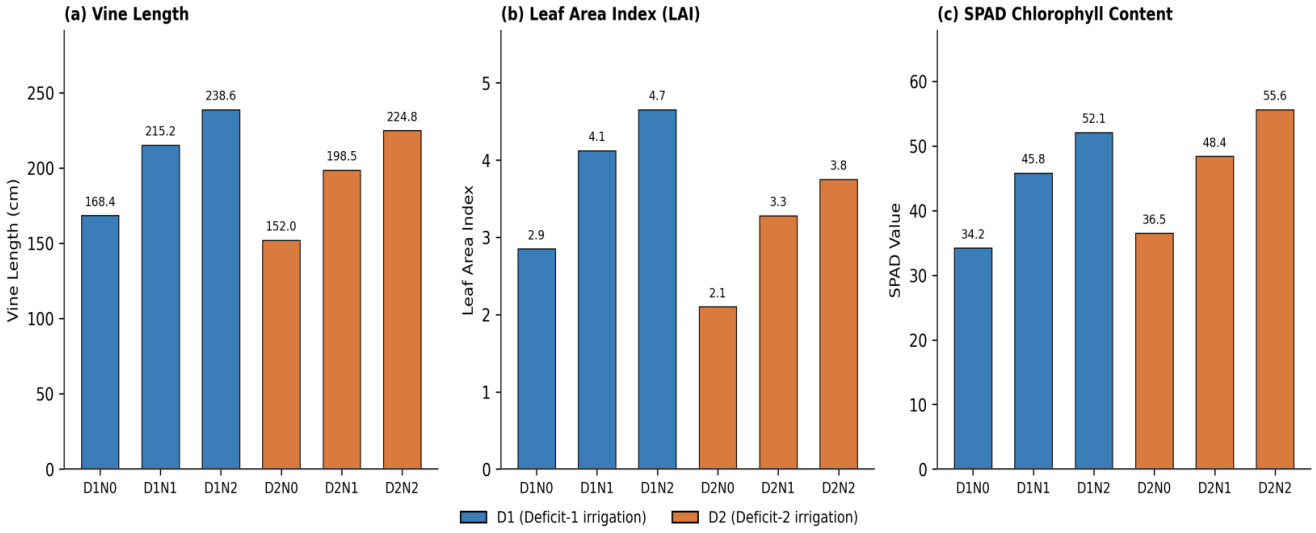


Figure 2. Effect of plant density and integrated nutrient regimes on vine growth parameters: (a) vine length, (b) leaf area index (LAI), and (c) SPAD chlorophyll content across plant density × nutrient regime treatment combinations.

3.2 Canopy Microclimate, Physiology, and Pest Dynamics

Plant density and integrated nutrient regimes significantly affected physiological processes, canopy microclimate, and fruit fly infestation (Figure 2). The greatest net photosynthetic rate was found in T6, (D2N2, 25.8 *u*mol m^{-2} s^{-1}) while the lowest was in T1, (D1N0, 14.2 *u*mol m^{-2} s^{-1}). Conversely Canopy Relative Humidity peaked in T3, (D1N2, 84.0%) and dropped to its lowest level in T4 (D2N0, 62.4%). The fruit fly infestation had a strong inverse relationship with the open canopy architecture (D2) which reduced the relative humidity and increased light penetration, creating an unfavorable microenvironment that affected fruit fly oviposition and reduced infestation. net photosynthesis high plant spacing (D1N0) lowered the relative humidity in the canopy, increasing the heat stress on the canopy, and increased the food availability for the pest. fruit fly

infestation canopy relative humidity (D1) reduced the intra canopy air circulation and trapped transpiration vapor, creating a dense and high humidity microclimate within the crop canopy, reducing the food availability for the pest. fruit fly infestation plant density (D1) lowered the intra canopy air circulation and trapped transpiration vapor, creating a dense and high humidity microclimate within the crop canopy, reducing the food availability for the pest.

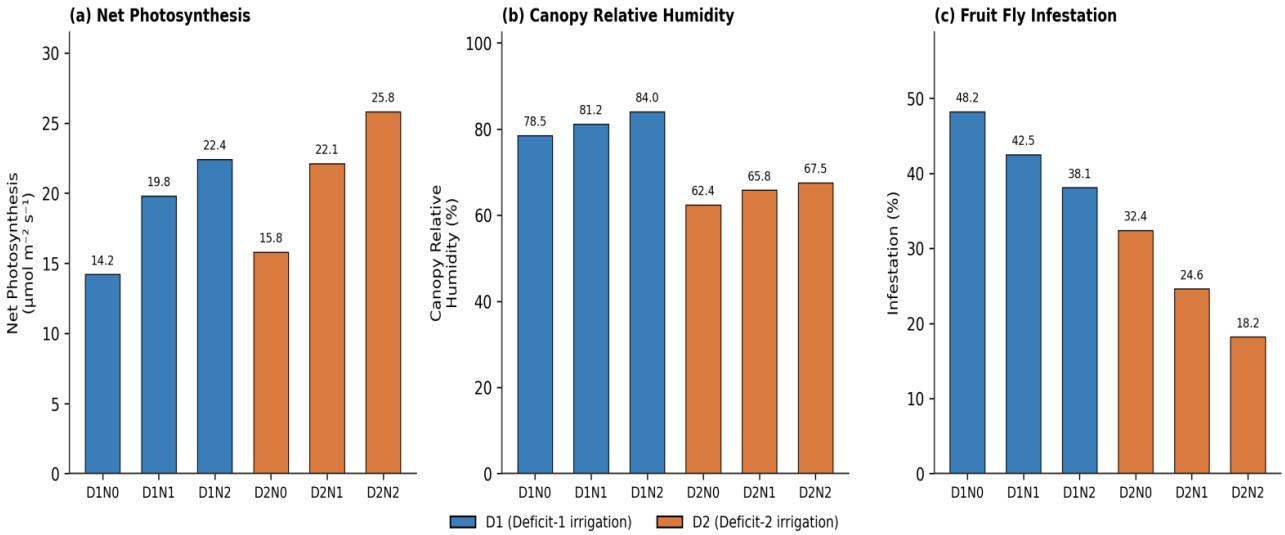


Figure 3. Effect of plant density and integrated nutrient regimes on physiological traits and pest infestation: (a) net photosynthesis rate, (b) canopy relative humidity, and (c) fruit fly infestation percentage across treatments.

3.3 Pest Population Dynamics and Yield Parameters

Plant density and integrated nutrient regimes (INR) influenced significantly pest pressure fruit development and marketable yield (Figure 3). Treatments T1 (D1N0, 6.8 larvae/fruit) had the highest Larval Density while the lowest intensity of treatments occurred in T6 (D2N2, 1.9 larvae/fruit). Similarly Aphid Population Density reached its peak in T1 (D1N0, 18.4 aphids/leaf) and dropped to a minimum in T6 (D2N2, 5.2 aphids/leaf). The wider plant spacing (D2) and better fertilization (N2) resulted in higher maggot densities per fruit, while the narrow plant spacing (D1) and less fertilization (N0) reduced maggot densities, thus reflecting the impact of different plant spacing and fertilization on Average Fruit Weight and Marketable Fruit Yield. larval density was greater in the denser plant canopies (D1) which provided an adequate humid microenvironment for fruit fly oviposition and larval survival inside the fruit tissues, compared to the wider plant spacing (D2), which significantly reduced maggot densities per fruit. Overall, wide spacing (D2) with balanced nutrition (N2) produced the best fruit growth rates, the low pest damage (less fruit fly infestation and larval populations) and the superior individual fruit development led to maximum marketable yield per hectare.

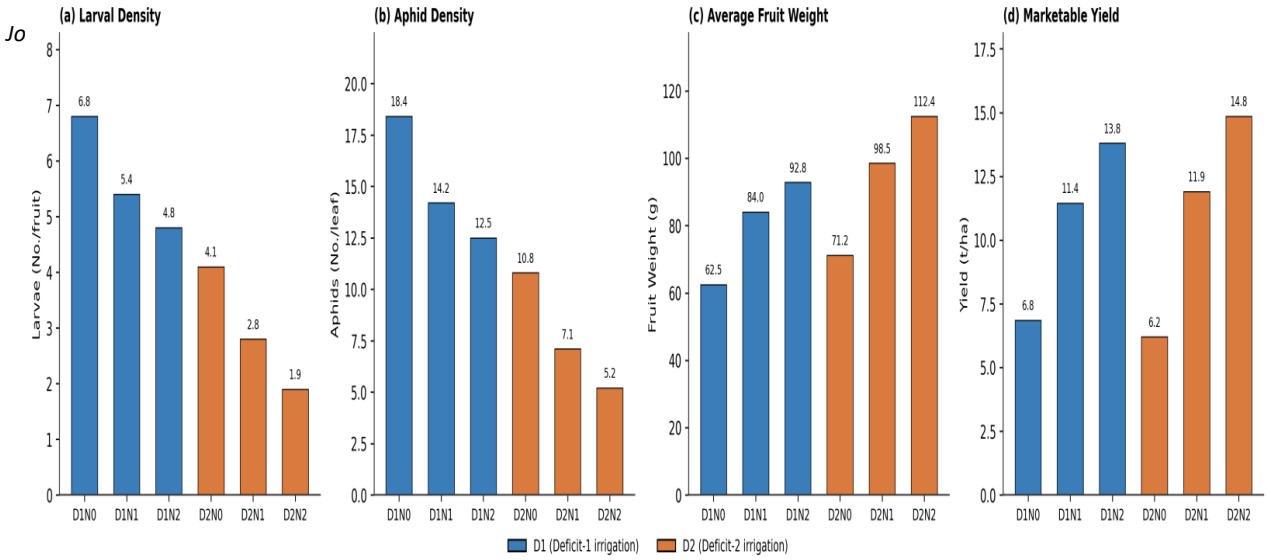


Figure 4. Effect of plant density and integrated nutrient regimes on pest density and yield attributes: (a) larval density, (b) aphid density, (c) average fruit weight, and (d) marketable yield across treatments.

3.4 Pearson Correlation Analysis among Growth, Physiological, Pest, and Yield Parameters

Physiological linkages and interactions between microclimate and pests were high and significant for all traits studied by Pearson correlation analysis (Figure 5). Marketable Yield was strongly positively correlated with the SPAD Chlorophyll (r = 0.99), Net Photosynthesis (r = 0.96), Vine Length (r = 0.95), Average Fruit Weight (r = 0.92), and LAI (r = 0.83). There was almost a perfect correlation between Net Photosynthesis and SPAD Chlorophyll (r = 0.99) and between Net Photosynthesis and Average Fruit Weight (r = 0.99). On the other hand, the Canopy Relative Humidity strongly positively correlated to the pest density measures such as Fruit Fly Infestation (r = 0.71), Larval Density (r = 0.67) and Aphid Density (r = 0.66). Therefore, there was a strong negative relationship between pest dynamics and physiological and yield characteristics; Net Photosynthesis was negatively correlated with Larval Density (r = -0.77), Aphid Density (r = -0.77), and Fruit Fly Infestation (r = -0.73), while Average Fruit Weight was negatively correlated with Aphid Density (r = -0.85), Larval Density (r = -0.84), and Fruit Fly Infestation (r = -0.81). The high correlations between SPAD Chlorophyll and Net Photosynthesis, Average Fruit Weight and Marketable Yield reveal that increased photosynthetic capability directly leads to increase in the allocation of assimilates to the fruit biomass and marketable yield output. The high positive correlation between Canopy Relative Humidity (CRH) and Fruit Fly Infestation (FFI), Larval Density (FD), and Aphid Density (APD) confirms the existence of favourably humid and dense canopy microclimates which provide an ecological niche for pest establishment and reproduction. The strong negative relationships between the pest metrics and fruit weight/yield illustrate the substantial indirect physiological loss from pest activity, as it hinders carbon assimilation and limits fruit development. pest damage on productivity.

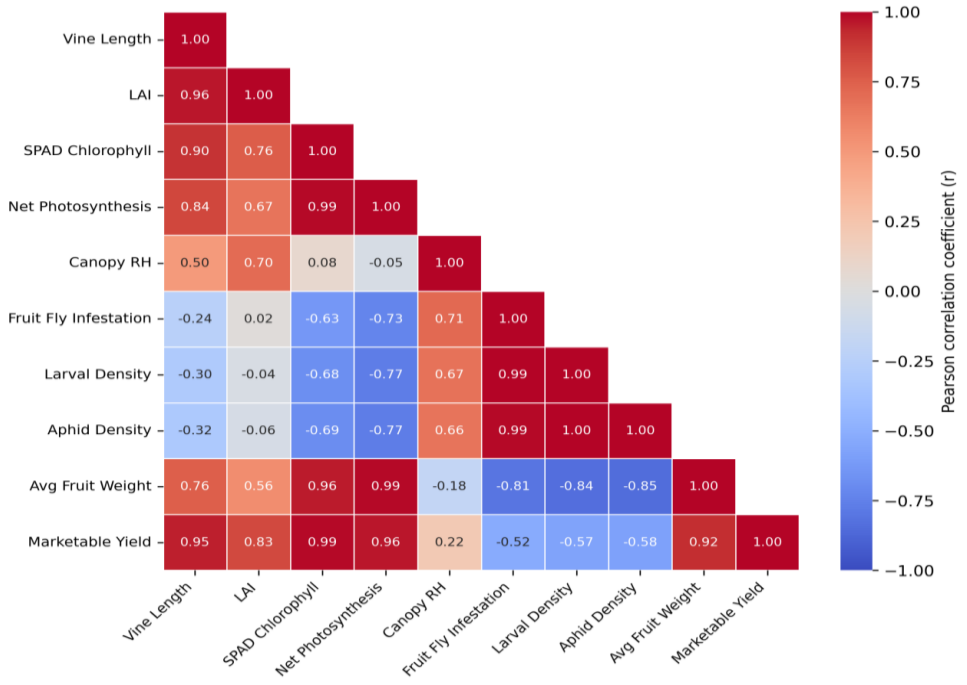


Figure 5. Heatmap showing the standardized (z-score) response of growth, physiological, pest, and yield parameters across plant density × nutrent regimes treatment combinations. Cell values represent actual measured data; color intensity indicates relative performance (green = higher, red = lower).

3.5 Comprehensive Heatmap Evaluation of Treatments Across Measured Parameters

Standardized heatmap analysis (z-score normalization) clearly distinguished the multidimensional performance of treatment combinations across growth, physiological, microclimatic, pest and yield parameters (Figure 4). High plant density combined with maximum fertilization (D1N2 / T3) displayed the highest standardized values for vegetative extension traits, including Vine Length (238.6 cm) and Leaf Area Index (4.6), alongside the highest Canopy Relative Humidity (84.0%). However wider plant spacing with enhanced nutrient application (D2N2 / T6) proved to be the most balanced and optimal treatment, exhibiting peak standardized scores for SPAD Chlorophyll (55.6), Net Photosynthesis (25.8 *u*mol m^{-2} s^{-1}) Average Fruit Weight (112.4 g), and Marketable Yield (14.8 t/ha). Concurrently, D2N2 achieved the lowest standardized values for pest severity, including Fruit Fly Infestation (18.2%), Larval Density (1.9 larvae/fruit), and Aphid Density (5.2 aphids/leaf). Conversely, control treatments under narrow spacing (D1N0 / T1) registered maximum pest pressures (48.2% infestation, 18.4 aphids/leaf) and poor physiological performance, while wider control plots (D2N0 / T4) yielded the absolute lowest Marketable Yield (6.2 t ha^{1}).

vegetative vs. reproductive superiority high density (D1) optimized biomass and leaf coverage (Vine Length and LAI), but wider spacing (D2) combined with integrated nutrition (N2) maximized single-plant physiological efficiency and reproductive output (Fruit Weight and Marketable Yield).

integrated microclimate and pest suppression the heatmap confirms that open canopy architecture (D2) maintains lower relative humidity (62.4% to 67.5%), effectively creating a stressful microenvironment for fruit fly and aphid buildup across all nutrient levels.

optimal agronomic synergy treatment D2N2 emerged as the overall superior management strategy, simultaneously optimizing light interception, photosynthesis, and nutrient utilization while providing natural cultural suppression of major insect pests.

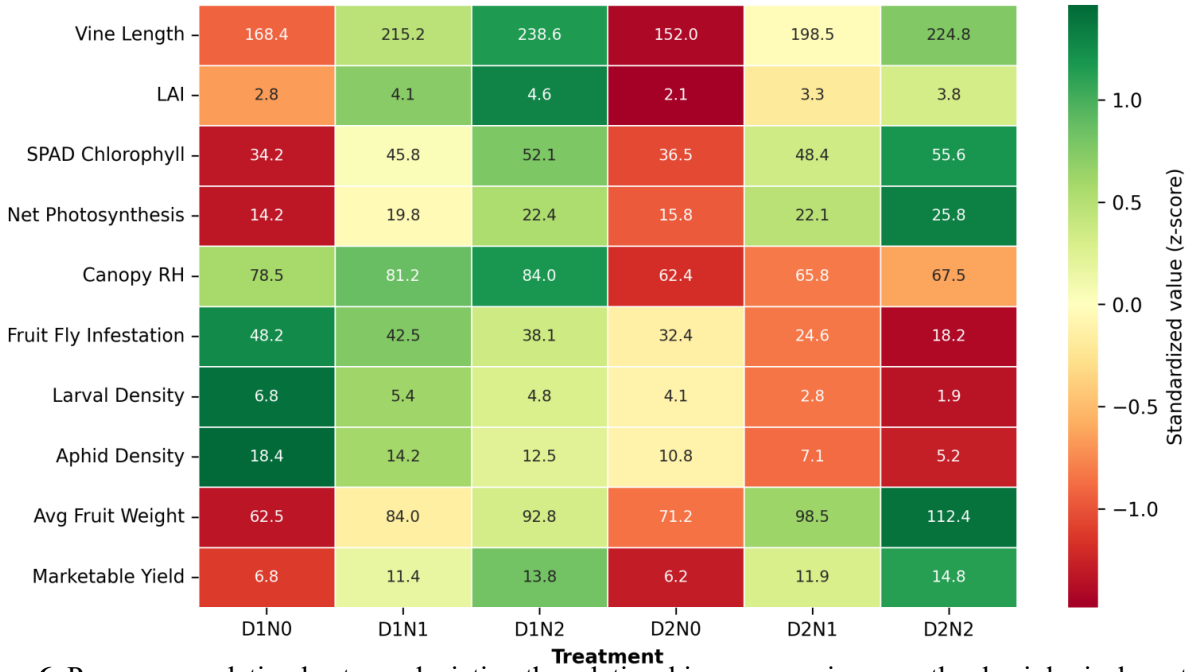


Figure 6. Pearson correlation heatmap depicting the relationships among vine growth, physiological, pest, and yield parameters (r = −1 to +1).

4. Discussion

The results show that integrated nutrient application was the main factor influencing the vegetative growth, and this effect was observed at both plant density levels, improving vine length, LAI and chlorophyll content, which has been supported by other studies on balanced N and micronutrient management and its effect on cell elongation, leaf expansion and chlorophyll biosynthesis (Bello et al., 2023 ; Zhang et al., 2025) But plant spacing definitely affected the response of this nutrient to yield. Close plant spacing favoured vigorous vegetative growth and helped to establish a relatively humid canopy microclimate, but this canopy humidity also seemed to favour fruit fly, larval counts, and aphid counts since the canopy relative humidity strongly positively correlated with all three pest indicators under high plant density (D1). This is in agreement with studies showing that canopy level humidity and aeration are major factors influencing insect pests' activity and development in vegetable crops, and that than the more dense and humid canopies tend to have higher insect pest pressure (Schöneberg et al., 2022; Fanourakis et al., 2026). Wider plant spacing (D2) however, reduced excessive vegetative crowding and reduced canopy humidity enough to keep pest numbers low, and this reduced fertilization to the same levels as D1 did not impair the photosynthetic capacity, as evidenced from net photosynthesis and SPAD when compared to D1 under fertilization at the same level. This aligns with the results of (Mubarak et al., 2022 ; Zheng et al., 2020) that open canopy management promotes sunlight access to lower leaves reducing mutual shading and thus maintaining active chlorophyll accumulation and photosynthetic efficiency per unit leaf area. This trend indicates a physiological mechanism whereby denitrification of intra

crop spatial competition with increased spacing led to greater transfer of photoassimilate toward fruit, similar to the results of canopy management in fruiting vegetable crops (Wang et al., 2020).

This resulted in greater fruit weight and marketable yield in D2N2 compared to the same spacing with D1N2, which had the longer vines, but yet fruit weight was not a good indicator of yield outcome where pest levels varied significantly between the two spacing treatments.

The strong negative correlations between pest metrics and both fruit weight and yield support the interpretation that pest suppression under wider plant spacing was a major contributor to the yield advantage of D2N2, in addition to the direct physiological benefit of micronutrient enriched fertilization. This has practical implications: combining wide plant spacing with integrated nutrient application offers a dual benefit of microclimate optimization and reduced reliance on chemical pest control, without compromising and in this case significantly improving marketable yield, mirroring conclusions from canopy management systems where optimal plant density combined with appropriate dosing sustained or enhanced fruit yield and quality (Wahsh et al., 2023). The poor performance of the non-fertilized treatments (D1N0, D2N0) across almost every parameter further confirms that spatial arrangement alone cannot compensate for inadequate nutrition, and that plant density and integrated nutrient regimes must be optimized jointly rather than independently.

The seasonal weather pattern offers additional context for these findings the prevailing environmental conditions likely intensified the microclimatic distinction between spacing regimes during early vine establishment, while mid season weather shifts may have influenced canopy relative humidity, explaining why the relative differences in pest indicators were modulated across nutrient levels. Overall, the combined evidence from growth, physiological, pest, and yield parameters, together with their inter correlations and the prevailing microclimatic conditions, supports D2N2 (wider plant spacing with integrated NPK + Zn + B) as the most agronomically favourable treatment combination evaluated in this study.

5. Conclusion

This study demonstrates that canopy microclimate modification via optimized plant density and integrated nutrient management is an effective strategy for suppressing insect pest infestation and enhancing yield in bitter gourd. High plant density, while promoting vegetative extension, creates a high-humidity microenvironment that exacerbates fruit fly and aphid pressure. Conversely, wider plant spacing (D2) improves canopy ventilation and reduces intra-crop competition for resources, which, when combined with integrated NPK and micronutrient (Zn, B) application (N2), significantly enhances photosynthetic efficiency and fruit development. The treatment combination D2N2 achieved the lowest pest severity and the highest marketable yield (14.8 t/ha), outperforming dense planting regimes. These results suggest that agronomists should prioritize open canopy architectures and balanced nutrition to reduce reliance on chemical pest control while maximizing productivity in cucurbitaceous crops.

Declaration

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Ethics approval/declaration: Ethical approval was not required for this study because it involved a field experiment on bitter gourd plants and did not involve human participants or animals.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Authors' contribution: Asma Saleem and Aneela Riaz contributed to the study design and manuscript preparation. Faisal Raza, Babar Ali, Rashid Khan and Umar Khitab Saddozai contributed to the research activities, data collection and manuscript revision. All authors reviewed and approved the final manuscript.

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