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Response of Integrated Pest Management Framework to Insect Pest Infestations of Tomato

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Abstract

Pests severely threaten tomato cultivation, prompting pesticide use that endangers health and the environment. To mitigate this problem, the investigation was conducted at the Gopalganj Science and Technology University, Gopalganj, Bangladesh in order to find out an integrated pest management (IPM) approach for controlling insect pests of tomato during October 2023 to April 2024 in accordance with randomized complete block design with three replications. One tomato variety cv. BARI tomato 2 was evaluated against the nine treatments viz. T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil (3 ml/L), T_3 = Vertical Support + Bishkatali (20 g/L), T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil, T_6 = Horizontal Support + Marshal 20EC (4 ml/L), T_7 = No Support + Bishkatali, T_8 = No Support + Marshal 20EC, and T_9 = Untreated Control. It was manifested that T_6 was the most effective, recording the lowest whitefly population during vegetative (3.07), early flowering (3.50), late flowering (5.67), early fruiting (3.77), late fruiting (3.50), and ripening (3.13) stages and highest yield (34.36 t/ha). Conversely, untreated control (T_9) had the highest whitefly population at all stages, with counts reaching 27.67 during late flowering and the lowest yield (15.94 t/ha). T_6 also resulted in the lowest fruit infestation by fruit borer (5.32%), compared to the highest infestation (24.41%) in T_9.

1. Introduction

Tomato (*Lycopersicon esculentum* Lin.), a vital member of the Solanaceae family, is one of the most widely cultivated and consumed vegetables worldwide. Renowned for its nutritional value, it is an excellent source of vitamins and minerals, particularly vitamin C, and is often called the "poor man's orange." Its versatility makes it a staple in various dishes, including salads, soups, pickles, ketchups, sauces, and juices [1-3].

In Bangladesh, tomatoes are predominantly grown during the Rabi season in home gardens and fields, reflecting their adaptability to diverse soils and climates. According to 2022-2023 period, tomato cultivation spanned approximately 64,000 acres, producing a total of 437,000 metric tons of tomatoes. This resulted in an average yield of around 6,828 kilograms per acre [4-6]. However, production has been significantly hampered by genetic deterioration of varieties, diseases, and insect pest infestations. Among the key challenges are whitefly (*Bemisia tabaci*) and tomato fruit borer infestations, which severely affect tomato productivity [7-9]. Whiteflies feed on the undersides of leaves, extracting sap and weakening plant vigor. Infested plants display chlorotic spots, wilting, and leaf shedding, leading to stunted growth and reduced yields [10]. The tomato fruit borer, a major pest, bores into fruits during the fruiting stage, feeding on internal tissues, causing deformities, reducing market value, and lowering seed viability [11,12]. Whiteflies can infest up to 50-60% of tomato crops, causing stunted growth, yellowing leaves, and reduced yield, particularly in areas with poor pest managements [13,14].

Insecticides play a vital role in agriculture by controlling pest populations, preventing crop damage, and ensuring higher yields. Pests can cause significant losses by damaging crops, spreading diseases, and competing for nutrients [15-16]. Insecticides help protect crops, control pest spread, and maintain food security [17]. They offer quick solutions, particularly during severe pest outbreaks when immediate action is needed [18-20]. However, it is essential to balance insecticide use with integrated pest management (IPM) strategies to minimize environmental and health risks [21-23]. Bioinsecticides, derived from natural sources like plants, bacteria, or fungi, provide an eco-friendly alternative. They target pests without harming beneficial insects, humans, or the environment [24]. Bioinsecticides help mitigate pesticide resistance, enhance IPM systems, and promote sustainable farming, reducing chemical dependence and protecting biodiversity [25].

The use of organic pesticides has several limitations. They are often less effective and slower acting than chemical alternatives, requiring more frequent applications [26,27]. Organic pesticides typically target fewer pests, limiting their use in controlling a wide range of insect species [28,29]. They can also be more expensive, particularly for large-scale farming [30]. Additionally, organic pesticides have a shorter residual effect, necessitating reapplication and providing less long-term protection. Availability can be a challenge in some regions, and improper use may still harm beneficial insects or pollinators [31,1].

Insecticides, when used alongside horizontal support (such as physical barriers, netting, or other mechanical methods), enhance the effectiveness of pest control strategies. This integrated approach, combining chemical and physical methods, provides more comprehensive pest management, reducing reliance on chemical insecticides alone and thus minimizing environmental and health risks [32]. Horizontal support can prevent pests from accessing crops, while insecticides target pests that bypass the physical barriers [33,34]. This dual strategy ensures better pest control, reduces crop damage, and improves yield.

Integrated Pest Management (IPM) has emerged as a practical, eco-friendly solution to pest control [35]. Rather than eradicating pests, IPM focuses on maintaining pest populations below economic thresholds [21,36,37]. This approach combines cultural, physical, biological, and mechanical control methods, with minimal reliance on chemical insecticides, ensuring sustainable pest management and environmental protection [38,39].

This study aimed to address the challenges of tomato pest management by evaluating the effectiveness of botanicals, synthetic insecticides, and mechanical support in controlling whitefly and fruit borer infestations. The research focused on identifying the most effective strategies to enhance tomato growth while minimizing health and environmental risks. The ultimate goal is to provide farmers with eco-friendly, cost-effective pest control solutions, promoting sustainable tomato production in Bangladesh. By achieving these objectives, the study aims to contribute to safer and more resilient agricultural practices.

2. Materials and Methods

2.1. Experimental Setup

The study was conducted at the Gopalganj Science and Technology University, Gopalganj, Bangladesh, during October 2023–April 2024. The experimental site is situated at 23°00' N latitude and 89°49' E longitude, with an elevation of approximately 12 meters above sea level [40] (Figure 1a). The charts depict monthly variations in humidity (%) and rainfall (mm) in Gopalganj. Humidity peaks in January and October, while rainfall is highest in October and minimal from November to March, reflecting the region's seasonal climatic trends (Figure 1b) [41].

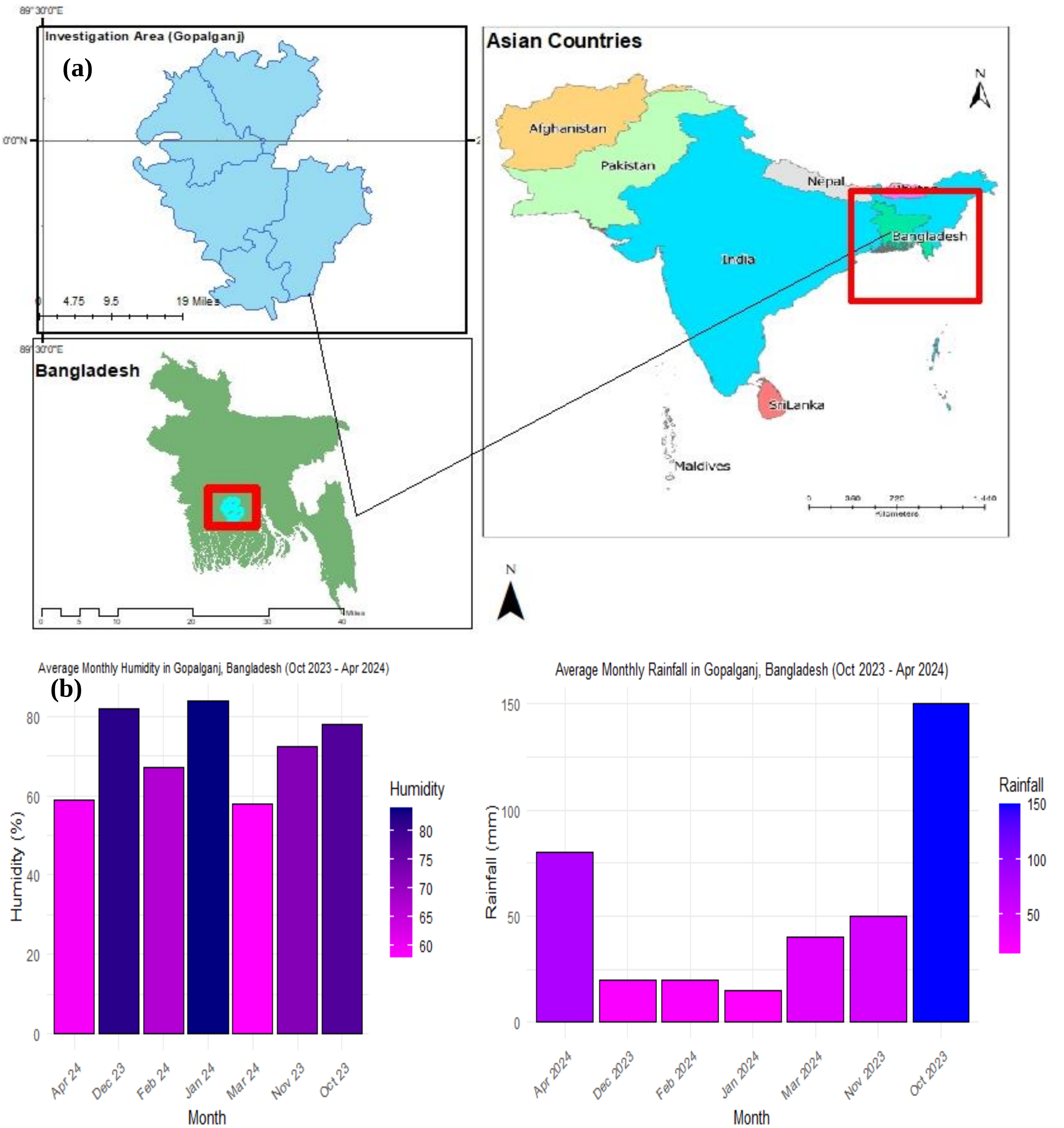

Figure (1): (a) Location of Investigation Area in Gopalganj, Bangladesh, Within Asian Context, and (b) Seasonal Trends of Humidity and Rainfall in Gopalganj, Bangladesh (Oct 2023 – Apr 2024).

The field is categorized under the Madhupur Tract of AEZ No. 28 and comprises dark grey terrace soil with low organic matter content. The land, classified as medium-high, was above flood levels and equipped with sufficient irrigation and drainage facilities to support the experiment. The plot received abundant sunlight throughout the study, ensuring favorable conditions for the research. The experimental soil offered optimal conditions for pest management in tomatoes, with all necessary resources in place to ensure accurate results. These factors collectively contributed to creating an ideal environment for evaluating integrated pest management strategies. In this study, tomato seeds of the BARI tomato 2 variety were sourced from the Bangladesh Agricultural Research Institute (BARI) and sown in a seedbed near the farmyard of Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj. Seedlings, aged 30 days, were transplanted for the experiment. The experiment followed a Randomized Complete Block Design (RCBD) with three replications and nine treatments, including a control. A total of 27-unit plots were prepared, each measuring 3 m × 1 m, with 1.0 m spacing between blocks and 0.5 m between plots. The treatments included various combinations: T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval T_3 = Vertical Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_6 = Horizontal Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_7 = No Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_8 = No Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_9 = Untreated Control.

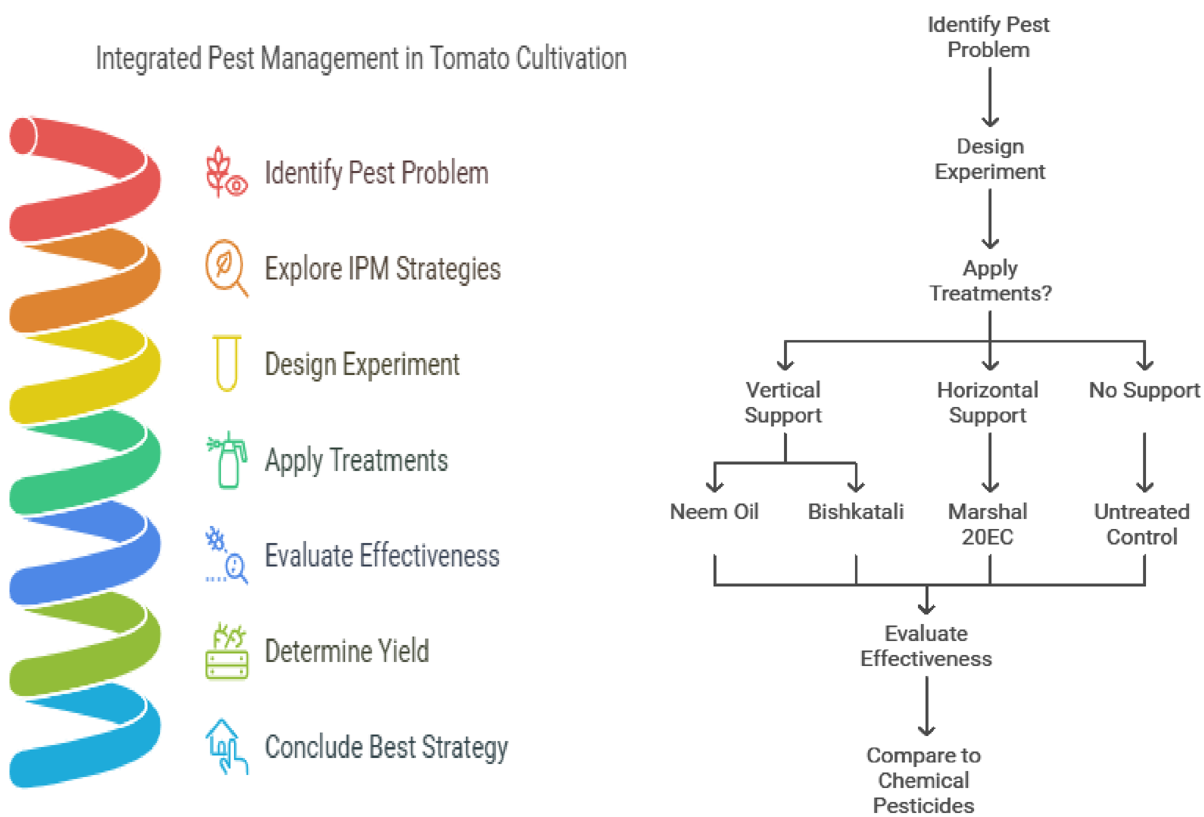

Figure (2): Overview of the experimental design and treatment applications.

2.2. Preparation of Seed and Land

Before sowing, tomato seeds were treated with Vitavex-200 at 0.25% to prevent soil-borne diseases, and Furadan 5G was applied at a rate of 1.2 kg/ha to protect against soil-dwelling insect pests. The seedbed, measuring 3 m × 1 m, was prepared in October 2023 for raising tomato seedlings. The soil was thoroughly ploughed and broken into loose, friable masses to achieve good tilth, ensuring proper aeration and drainage. All weeds, stubbles, and dead roots were removed, and cow dung was applied at a rate of 10 t/ha to improve soil fertility. For the experimental field, land preparation began in early October with a power tiller, exposing the soil to sunlight for one week to eliminate pests and pathogens. This was followed by repeated harrowing, ploughing, and crossploughing, with laddering to refine the soil structure. The field was then partitioned into unit plots according to the experimental design, ensuring uniformity.

2.3. Collecting Data

Data were collected on the incidence of whitefly, leaf miner, and fruit borer infestations, along with observations on infested and healthy fruits, yield-contributing traits, and overall tomato yield.

Whitefly infestation was monitored by five plants from each plot were randomly tagged. Five fully expanded compound leaves from the top, middle, and bottom sections of each plant were inspected without disturbing the plant. Observations were conducted at 10-day intervals, beginning from the vegetative stage and continuing through the ripening stage, until the final fruit harvest. The number of whiteflies per leaf was recorded during each observation [42,43].

The total number of fruits and bored (infested) fruits were counted during each harvest. Observations were pooled across all harvests and expressed as a percentage of infested fruits. Infestation was identified by the visible holes created by larvae. The percentage of borer-infested fruits was calculated using following formula [44]:

$$\textbf{Borer infested fruits (By number)}\% = \frac{\textbf{Number of Infested Fruits}}{\textbf{Total number of fruits}} \times \textbf{100}\%$$

$$\textbf{Borer infested fruits (By weight)}\% = \frac{\textbf{Weight of infested fruits}}{\textbf{Total weight of fruits}} \times \textbf{100}\%$$

The number of the healthy and infested fruit were counted at each harvest and continued up to the last harvest from the plants. Healthy fruits recorded at each observation were pooled and finally expressed in percentage.

2.4. Statistical Analysis

The recorded data were compiled and tabulated for statistical analysis. Analysis of variance was done with the help of computer package MSTAT program. The treatment means were separated by Duncan‟s Multiple Range Test (DMRT).

3. Results

The experiment, conducted at Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj, Bangladesh, aimed to develop an IPM strategy for tomato pest control, focusing on whitefly, fruit borer impact, yield, and contributing factors.

3.1. Number of Whiteflies

Whitefly populations showed notable differences across the various growth stages of tomatoes. During the vegetative phase, the lowest count (3.07) was recorded in the T_6 plots (Marshal 20EC at 4.0ml/L with vertical support at 7-day intervals), which was statistically similar to T_8 (3.40; Marshal 20EC at 4.0ml/L without support). Neem oil treatments, T_2 (4.57; Neem oil at 3ml/L with vertical support) and T_5 (4.63; Neem oil at 3ml/L with horizontal support), demonstrated moderate effectiveness, while untreated plots (T_9) had the highest count (21.97) (Table 1).

During the early flowering stage, T_6 showed the lowest count at 3.50, which was statistically comparable to T_8 at 3.93, while the untreated plots displayed the highest count of 23.87. This pattern continued into the late flowering stage, where T_6 recorded a count of 5.47 and T_8 had 5.17, both being the lowest, whereas untreated plots reached a peak of 27.67 (Table 1).

In the early fruiting stage, T_6 (3.77) and T_8 (4.03) proved to be the most effective treatments, while untreated plots showed the highest count (24.10). During the late fruiting phase, T_6 (3.50) and T_8 (3.93) still exhibited the lowest numbers, whereas untreated plots (23.23) recorded significantly higher counts. As the fruit ripened, T_6 (3.13) and T_8 (3.67) retained their effectiveness, in contrast to the highest count found in untreated plots (22.39). Marshal

20EC (@ 3.0ml/L with vertical or no support, applied weekly) successfully lowered whitefly populations, likely due to its systemic action and rapid knockdown characteristics throughout the growing season (Table 1).

Table (1): Effect of different control approaches against whitefly in the tomato field per plot during the cultivation and fruit infestation by number at early fruiting stage.

Treatments	No. of Whitefly/plot						Tomato fruit by number			
	Vegetative Stage	Flowering stage		Fruiting Stage		Fruit ripening Stage				
		Early	Late	Early	Late		Healthy	Infested	Infestation %	Infestation decreases over control %
T_1	7.67 c	11.90 c	15.90 c	12.23 c	10.23 c	9.43 c	13.87 cd	2.80 b	19.01 bc	37.15 ef
T_2	4.57 f	5.57 e	6.20 f	5.57 f	4.90 ef	4.27 e	16.10 a	1.50 de	10.69 ef	52.07 bc
T_3	4.97 de	5.98 d	7.97 de	6.47 de	4.77 de	4.80 d	15.33 bc	2.59 bcd	11.71 d	45.91 d
T_4	11.03 b	13.57 b	16.83 b	12.53 b	11.67 b	11.07 b	13.53 cd	2.63 ab	20.58 b	27.62 f
T_5	4.63 ef	6.10 e	7.58 ef	5.73 ef	5.27 e	4.67 e	17.83 ab	2.13 cde	12.53 e	60.56 c
T_6	3.07 g	3.50 f	5.47 g	3.77 g	3.50 g	3.13 f	19.97 a	1.63 f	8.28 g	78.12 a
T_7	6.18 d	7.37 d	7.88 d	6.17 d	6.67 d	6.27 d	12.17 c	2.15 bc	15.81 cd	31.29 de
T_8	3.40 g	3.93 f	5.17 g	4.03 g	3.93 fg	3.67 f	17.60 a	1.67 ef	8.49 fg	71.76 ab
T_9	21.97 a	23.87 a	27.67 a	24.10 a	23.23 a	22.39 a	12.07 d	3.33 a	22.43 a	--
LSD (0.05)	0.95	0.67	0.68	0.91	1.18	0.82	2.52	0.45	2.60	10.03
CV (%)	7.35	4.33	3.64	6.02	7.32	6.32	9.78	11.95	11.14	12.10

In a column means having similar letter(s) are statistically identical and those having dissimilar letter(s) differ significantly as per 0.05 level of probability. T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_3 = Vertical Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_6 = Horizontal Support + Marshal 20EC @4 ml/L of water 5 times at 7 days interval, T_7 = No Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_8 = No Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_9 = Untreated Control.

3.2. Fruit Borer Infestation

The trial demonstrated considerable differences in the numbers of healthy versus infested fruits, as well as the percentage of fruit infestation, during the initial fruiting phase of tomato growing when various IPM practices were employed. Treatment T_6 recorded the greatest quantity of healthy fruits per plot (19.97), which was statistically comparable to T_8 (17.60), followed by T_5 (17.83) and T_2 (16.10). Treatment T_9 had the least number of healthy fruits (12.07), whereas T_6 exhibited the lowest count of infested fruits (1.63), which was statistically similar to T_8 (1.67). The percentage of fruit infestation was the lowest in T_6 at 8.28%, and the highest was found in T_9 at 21.43%. T_6 accomplished the most significant reduction in infestation at 78.12% as listed in Table (1).

Notable differences in the weights of healthy and infested fruits and the percentage of infestation were detected at the initial fruiting stage when applying IPM strategies against the tomato fruit borer. Treatment T_6 exhibited the highest weight of healthy fruit per plot (2149.20 g), which was statistically comparable to T_8 (2111.90 g), T_2 (1917.60 g), and T_5 (1929.10 g). The untreated control (T_9) yielded the lowest weight of healthy fruit (1058.40 g). In addition, T_6 exhibited the lowest weight of infested fruit (98.33 g) and the lowest infestation rate (6.98%), with T_8 following closely at 7.91%. Greatest reduction in infestation was seen in T_6 (75.39%), whereas T_4 had the least reduction (29.14%). T_6 displayed the most effective performance in reducing infestation as tabulated in Table (2).

Table (2): Effect of different control practices on fruit infestation by weight at early fruiting stage and fruit infestation by number at mid fruiting stage.

Treatments	Tomato fruit by weight (g)				Tomato fruit by number			
	Healthy	Infested fruit	Infestation %	Infestation decreases over control %	Healthy	Infested	Infestation %	Infestation decreases over control %
T_1	1325.70 def	243.90 b	16.98 b	37.69 e	24.67 de	4.07 a	13.58 b	37.47 c
T_2	1917.60 ab	123.80 d	9.42 de	68.64 bc	25.07 bc	2.83 cd	9.64 cde	66.07 ab
T_3	1302.20 bcd	217.80 bc	10.35 c	52.87 d	27.13 cd	3.37 bc	11.89 c	54.22 b
T_4	1255.30 ef	248.10 ab	16.72 b	27.14 e	22.33 e	3.53 a	15.39 b	29.14 c
T_5	1929.10 abc	196.47 cd	10.40 d	63.46 c	25.70 bc	2.93 bcd	10.32 cd	62.65 ab
T_6	2149.20 a	98.33 e	5.32 f	82.30 a	33.33 a	2.32 d	6.98 e	75.39 a
T_7	1544.10 cde	217.00 bc	13.96 c	41.23 d	23.60 cd	3.40 b	12.47 c	51.11 b
T_8	2011.90 a	159.33 de	8.76 ef	75.97 ab	30.80 ab	2.63 d	7.91 e	58.58 a
T_9	1058.40 f	262.13 a	24.41 a	--	17.60 f	4.70 a	23.02 a	--
LSD (0.05)	303.20	40.37	2.47	9.87	3.46	0.59	2.63	13.15
CV (%)	12.23	12.65	11.44	10.78	8.02	10.82	12.90	15.27

In a column means having similar letter(s) are statistically identical and those having dissimilar letter(s) differ significantly as per 0.05 level of probability. T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_3 = Vertical Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_6 = Horizontal Support + Marshal 20EC @4 ml/L of water 5 times at 7 days interval, T_7 = No Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_8 = No Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_9 = Untreated Control.

The trial revealed considerable differences in the counts of healthy and infested fruits, as well as the percentage of infestation, during the mid-fruiting stage of tomato cultivation using IPM methods. Treatment T_6 yielded the highest number of healthy fruits (33.33), which was statistically comparable to T_8 (30.80), while T_9 reported the lowest count (17.60). Additionally, T_9 exhibited the highest number of infested fruits (4.70), followed by T_4 (3.53) and T_1 (4.07). T_6 recorded the fewest infested fruits (2.32) and the lowest percentage of infestation (6.98%), which was statistically similar to T_8 (7.91%) and T_2 (9.64%). Treatment T_6 demonstrated the most significant reduction in infestation (82.30%), corroborating the findings of Ali et al. (2009) that integrated strategies are effective in managing fruit borers (Table 2).

The trial revealed considerable differences in the counts of healthy and infested fruits, as well as the percentage of infestation, during the mid-fruiting stage of tomato cultivation using IPM methods. Treatment T_6 yielded the highest number of healthy fruits (33.33), which was statistically comparable to T_8 (30.80), while T_9 reported the lowest count (17.60). Additionally, T_9 exhibited the highest number of infested fruits (4.70), followed by T_4 (3.53) and T_1 (4.07). T_6 recorded the fewest infested fruits (2.32) and the lowest percentage of infestation (6.98%), which was statistically similar to T_8 (7.91%) and T_2 (9.64%). Treatment T_6 demonstrated the most significant reduction in infestation (82.30%), corroborating the findings of Ali et al. (2009) that integrated strategies are effective in managing fruit borers as shown in Table (2).

The research demonstrated notable variations in the weights of healthy and infested fruits as well as in the percentage of infestation at the mid-fruiting stage when utilizing IPM methods for controlling tomato fruit borer. Among the treatments, T6 exhibited the greatest healthy fruit weight (3346.30 g), which was statistically comparable to T8 (3076.70 g), while the untreated control (T9) showed the least healthy fruit weight at 1538.20 g. Additionally, T6 recorded the lowest weight of infested fruit (198.80 g) and the smallest percent infestation (7.43%), with T8 following closely at 7.62% and T2 at 8.55%. T6 also achieved the most reduction in infestation compared to the control (81.15%), validating its efficacy in reducing damage from fruit borers (Table 3).

The trial indicated notable differences in the quantities of healthy and infested fruits, as well as the percentage of fruit infestation during the late fruiting stage of tomatoes utilizing IPM practices. Treatment T6 showed the highest count of healthy fruits (46.20), which was statistically comparable to T8 (40.33), whereas T9 had the lowest count (27.83), followed by T4 (31.70) and T1 (30.87). Additionally, T6 had the fewest infested fruits (2.90) and the lowest percentage of infestation (4.69%), which was statistically similar to T8 (5.23%), T2 (5.50%), and T5 (6.96%). Conversely, T9 had the highest percentage of infestation (18.00%). T6 demonstrated the most substantial reduction in infestation (69.96%), highlighting its effectiveness in combating fruit borers (Table 3).

Table (3): Effect of different control practices on fruit infestation by weight at mid fruiting stage and fruit infestation by number of tomatoes at late fruiting stage.

Treatments	Tomato fruit by weight (g)				Tomato fruit by number			
	Healthy	Infested fruit	Infestation %	infestation decrease over control %	Healthy	Infested	Infestation %	Infestation decreases over control %
T_1	2147.30 de	330.00 b	14.76 b	41.12 c	30.87 de	4.50 bc	13.38 b	37.15 e
T_2	2824.70 bc	240.40 de	8.55 cde	73.55 ab	35.80 bc	3.37 def	5.50 cd	50.49 abc
T_3	2183.70 c	288.20 c	10.86 c	49.53 b	36.93 cd	3.17 de	10.09 c	52.60 cd
T_4	1922.40 ef	290.20 ab	14.75 b	30.80 c	31.70 e	4.70 ab	11.74 b	23.28 e
T_5	2732.90 bc	247.10 cd	10.33 cd	64.69 ab	39.40 bc	3.43 def	6.96 cd	58.04 bcd
T_6	3346.30 a	198.80 e	7.43 e	81.15 a	46.20 a	2.90 f	4.69 d	69.96 a
T_7	2514.50 cd	286.10 c	12.06 c	58.66 b	35.83 cd	3.83 cd	10.75 c	49.34 d
T_8	3076.70 ab	233.73 de	7.62 de	75.14 a	40.33 ab	3.03 ef	5.23 d	59.45 ab
T_9	1538.20 f	377.70 a	23.23 a	--	27.83 e	5.37 a	18.00 a	--
LSD (0.05)	386.00	43.65	2.52	12.56	4.86	0.69	2.19	11.14
CV (%)	9.61	9.74	13.30	13.23	8.23	11.26	12.76	13.71

In a column means having similar letter(s) are statistically identical and those having dissimilar letter(s) differ significantly as per 0.05 level of probability. T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_3 = Vertical Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_6 = Horizontal Support + Marshal 20EC @4 ml/L of water 5 times at 7 days interval, T_7 = No Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_8 = No Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_9 = Untreated Control.

Notable variations were found in the weights of healthy versus infested fruits and the percentage of infestation during the late fruiting phase under integrated pest management strategies for controlling the tomato fruit borer. Treatment T6 recorded the highest weight of healthy fruits at 4515.50 g, which was statistically comparable to T8 at 4182.30 g. In contrast, T9 exhibited the lowest weight at 1776.40 g, followed by T4 with 2667.70 g.

Furthermore, T6 also had the lowest weight of infested fruits at 187.00 g and the lowest infestation percentage at 3.79%, followed by T8 at 6.59% and T2 at 7.48%. The highest percentage of infestation was noted in the untreated control group (T9) at 19.18%. T6 demonstrated the greatest reduction in infestation at 79.83%, proving its effectiveness (see Table 4).

3.3. Fruits Bearing Status of Tomato

According to Table (4), treatment T_6 yielded the highest number of fruits per plot, totaling 102.40, followed closely by T_8 at 98.86, with T_2 at 93.47 and T_5 at 89.42. The untreated control, T_9, had the fewest fruits at 60.30. T_6 also produced the greatest number of healthy fruits, reaching 99.40, followed by T_8 with 95.33, whereas the untreated control recorded the lowest at 49.70. The fewest infested fruits were found in T_6 (5.89), next was T_8 (6.29). T_6 exhibited the lowest percentage of fruit infestation at 5.32%, while the untreated control had the highest at 21.42%. T_6 demonstrated the most significant decrease in infestation, achieving a reduction of 72.71%.

3.4. Yield of Tomato

The various management practices had a considerable impact on tomato yield, as illustrated in Table (4). When expressed in ton/ha, T_6 achieved the highest yield at 34.36 ton/ha, with T_8 following closely at 32.08 ton/ha, while T_9 had the lowest yield at 15.94 ton/ha.

Table (4): Effect of different control practices on fruit infestation by weight of tomato at late fruiting stage and different control practices in controlling tomato fruit borer in terms of fruits per plot in number during total cultivation period.

Treatments	Tomato fruit by weight (g)				Tomato fruit by number			
	Healthy	Infested fruit	Infestation %	Infestation decrease over control %	Healthy	Infested	Infestation %	Infestation decreases over control %
T_1	2147.30 de	330.00 b	14.76 b	41.12 c	30.87 de	4.50 bc	13.38 b	37.15 e
T_2	2824.70 bc	240.40 de	8.55 cde	73.55 ab	35.80 bc	3.37 def	5.50 cd	50.49 abc
T_3	2183.70 c	288.20 c	10.86 c	49.53 b	36.93 cd	3.17 de	10.09 c	52.60 cd
T_4	1922.40 ef	290.20 ab	14.75 b	30.80 c	31.70 e	4.70 ab	11.74 b	23.28 e
T_5	2732.90 bc	247.10 cd	10.33 cd	64.69 ab	39.40 bc	3.43 def	6.96 cd	58.04 bcd
T_6	3346.30 a	198.80 e	7.43 e	81.15 a	46.20 a	2.90 f	4.69 d	69.96 a
T_7	2514.50 cd	286.10 c	12.06 c	58.66 b	35.83 cd	3.83 cd	10.75 c	49.34 d
T_8	3076.70 ab	233.73 de	7.62 de	75.14 a	40.33 ab	3.03 ef	5.23 d	59.45 ab
T_9	1538.20 f	377.70 a	23.23 a	--	27.83 e	5.37 a	18.00 a	--
LSD (0.05)	386.00	43.65	2.52	12.56	4.86	0.69	2.19	11.14
CV (%)	9.61	9.74	13.30	13.23	8.23	11.26	12.76	13.71

In a column means having similar letter(s) are statistically identical and those having dissimilar letter(s) differ significantly as per 0.05 level of probability. T_1 = Vertical Support, T_2 = Vertical Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_3 = Vertical Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_4 = Horizontal Support, T_5 = Horizontal Support + Neem Oil @ 3 ml/L of water 5 times at 7 days interval, T_6 = Horizontal Support + Marshal 20EC @4 ml/L of water 5 times at 7 days interval, T_7 = No Support + Bishkatali @ 20 gm/L of water 3 times at 3 days interval, T_8 = No Support + Marshal 20EC @ 4 ml/L of water 5 times at 7 days interval, T_9 = Untreated Control.

Correlation studies were conducted to examine the relationships between fruit infestation and yield at different fruiting stages, as well as between fruit weight and the number of fruits per plot with yield in tomato during the management of fruit borer.

At the early fruiting stage, a significant negative correlation was observed between fruit infestation and yield, with the regression equation y = -0.2652x + 11.054 (R^2 = 0.9774) and y = -0.3082x + 11.103 (R^2 = 0.9542), indicating that an increase in fruit infestation resulted in a decrease in yield. A similar negative relationship was observed at the mid and late fruiting stages, with regression equations y = -1.037x + 37.2 (R^2 = 0.957) and y = -0.3915x + 11.359 (R^2 = 0.9618), respectively, showing that higher infestation levels at these stages also led to reduced yields (Figure 3a & b).

In contrast, a significant positive correlation was found between fruit weight per plot and yield, with the regression equation y = 0.0026x + 1.3838 (R^2 = 0.9943). This suggests that an increase in fruit weight per plot directly contributed to a higher yield. Similarly, the relationship between the number of fruits per plot and yield was also positive, as shown by the regression equation y = 0.438x – 11.37 (R^2 = 0.992). These findings indicate that a higher number of fruits per plot led to an increase in yield. Overall, the study demonstrated that minimizing fruit infestation and maximizing fruit weight and number were key to optimizing tomato yield under integrated pest management practices (Figure 3c, d, & e).

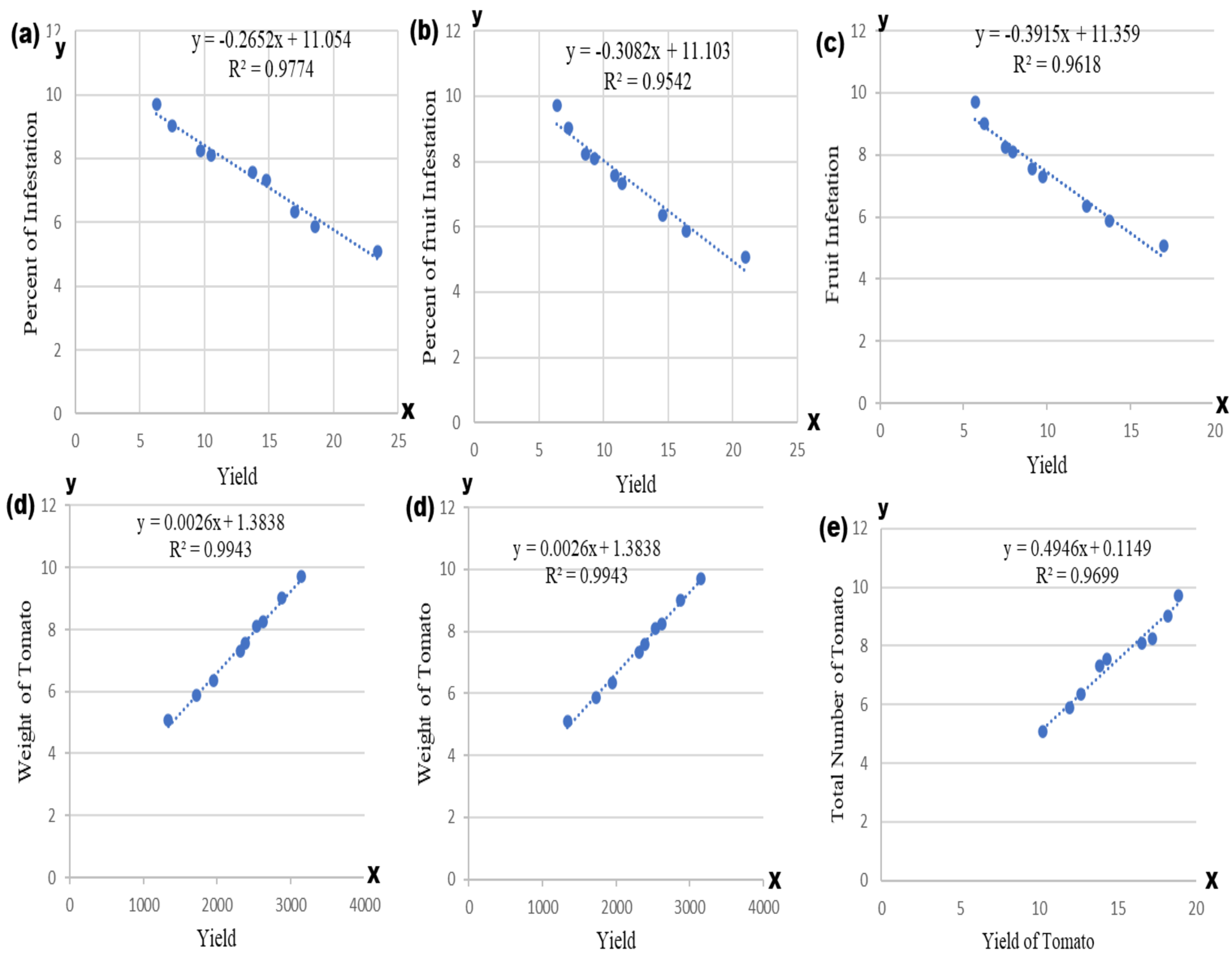

Figure (3): Regression between different variables in investigation, (a) Relationship between percent fruit infestation by number and yield at early fruiting stage, (b) Relationship between percent fruit infestation by number and yield at mid fruiting stage, (c) Relationship between percent fruit infestation by number and yield at late fruiting stage, (d) Relationship between fruit weight per plot and yields, and (e) Relationship between fruit per plot and yield. Here, x axis is independent variable and y axis dependent variable.

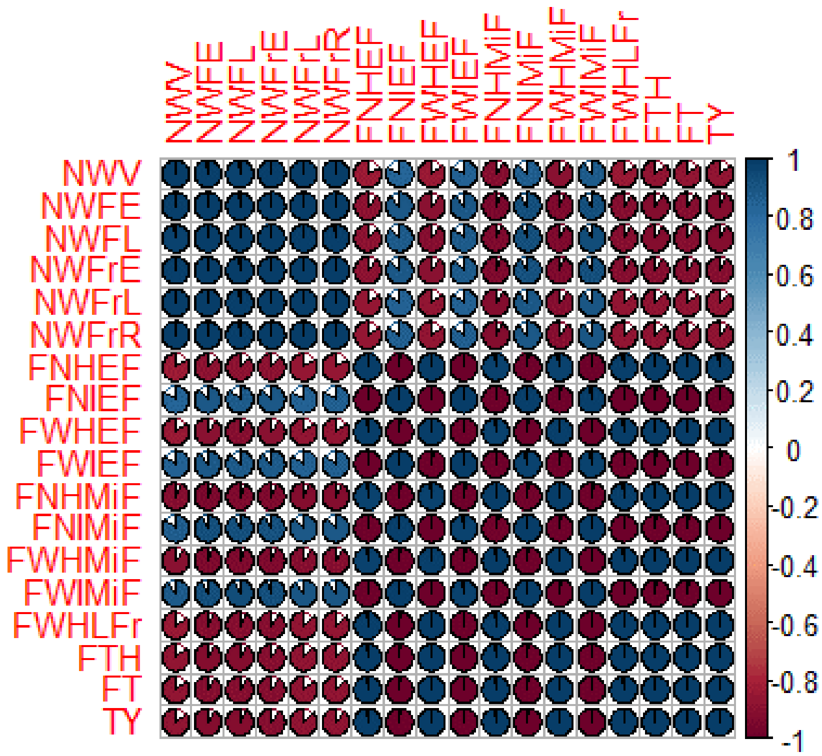

Figure (4): Correlation of different variables of tomato. Here NWV, number of whitefly at vegetative stage, NWFE, number of whitefly early fruiting, NWFL, number of whitefly late fruiting; NWFrE, number whitefly early fruiting; NWFrL, number of white fruit late fruiting, NWFrR, number of whitefly fruit ripenning, FNHEF, healthy fruit numbrt at early fruiting; FWHEF, healthy fruit weight at early fruiting; FWIEF, fruit weight incidence at early fruiting; FNHMiF, healthy fruit number at mid fruiting stage; FNMiF, fruit number at mid fruiting; FWIMiF, fruit weight incidence at mid fruiting ; FTH, healty total fruit; FT, total fruit; TY, total yield.

The scatter plot revealed that most parameters in the study exhibited highly significant relationships with other parameters, demonstrating that all treatments interacted effectively and produced significant results across all comparisons. Pearson's method was employed for this analysis (Figure 4).

The PCA analysis revealed that the first two principal components (PC1 and PC2) accounted for 94.6% and 4.7% of the total variance, respectively, highlighting the dominance of PC1 in explaining the majority of the dataset's variability. In the individuals PCA plot, treatments were distributed along the principal components, with treatments 6 and 8 positioned far along the positive axis of PC1, indicating their strong contribution to the variance and superior performance in the study. In contrast, treatment 9 was located in the negative direction of PC1, reflecting its weaker contribution. Treatments near the origin, such as T_1, T_2, and T_3, showed moderate contributions with less differentiation in performance. Treatments positioned closer to the x-axis demonstrated stronger alignment with the dominant variability explained by PC1 (Figure 5a).

The PCA biplot further illustrated the relationships between variables and treatments. Key variables such as FWHLF (Healthy fruit weight of late fruiting stage), FNHEF (healthy fruit number of early fruiting), and FT (total fruit) aligned closely with PC1, showing a strong positive correlation with treatments like T_6 and T_8, which contributed to their significant outcomes. Variables near the origin had minimal influence, while those associated with PC2, such as FNIiEF (number of infested fruits at early fruiting) and FWIMiF (fresh weight of infested fruits at mid fruiting), explained less variability. Treatment 9, positioned negatively along PC1, was associated with lower values of the primary contributing variables.

Overall, the analysis underscores the importance of PC1 in capturing the dominant variability in the dataset, with treatments 6 and 8 emerging as the most impactful. Variables such as FWHLF, FNHEF, and FT played a critical role in driving these significant results, providing valuable insights for future research and optimization strategies.

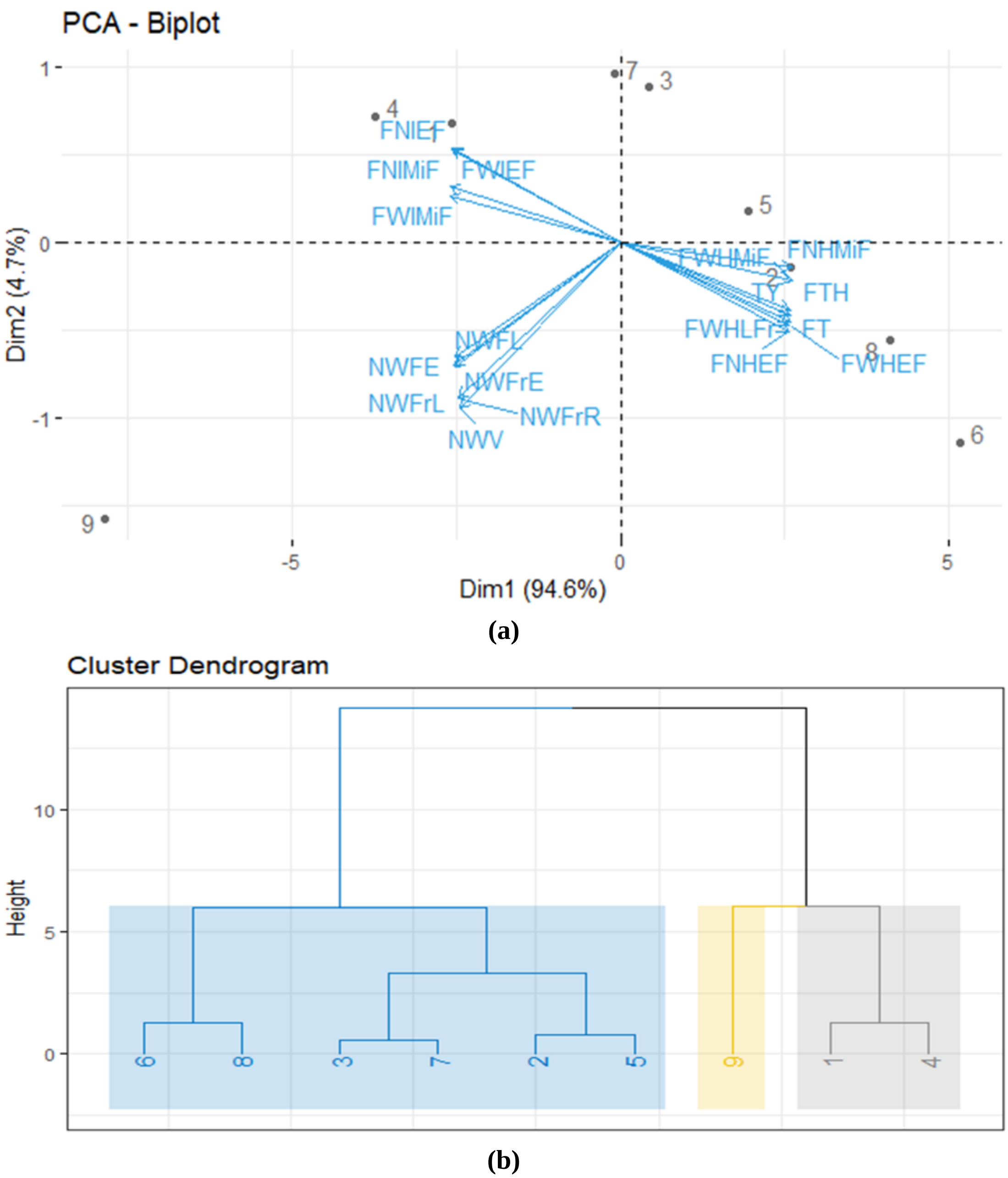

Figure (5): (a) Principal Component Analysis of different parameters and different treaments; (b) cluster analysis of different treatment of experiment.

In the cluster analysis, the Ward's agglomerative coefficient was calculated, yielding a value of 0.892, which is close to 1.00, indicating a highly significant result for this investigation. Three distinct groups were formed, each showing significant outcomes. Among all treatments, treatments 6 and 8 demonstrated the best results, making them particularly noteworthy for this study (Figure 5b).

The findings presented in Table (3) highlight notable differences among treatments in terms of fruit infestation by weight and number during the mid and late fruiting stages. Treatment T6 consistently outperformed all others, achieving the lowest infestation levels and highest healthy fruit production. T8 and T2 also demonstrated substantial effectiveness, though slightly less than T6. In contrast, the untreated control (T9) exhibited the highest infestation rates and the lowest yield parameters. These results underscore the superior impact of integrating horizontal support with Marshal 20EC for minimizing fruit borer damage and enhancing overall tomato productivity.

4. Discussions

The present study evaluated the efficacy of various integrated pest management (IPM) practices in controlling whiteflies and fruit borers in tomato cultivation. The findings highlighted significant variations in pest numbers, fruit infestation, and yield under different treatments, with T_6 (Marshal 20EC @ 4.0 ml/L + vertical support, applied at 7-day intervals) consistently demonstrating superior performance across all parameters.

Whitefly counts varied across growth stages, with T_6 consistently recording the lowest numbers, statistically comparable to T_8 (Marshal 20EC @ 4.0 ml/L + no support). The systemic action and rapid knockdown properties of Marshal 20EC appear to be the primary contributors to its effectiveness. Neem oil treatments (T_2 and T_5) showed moderate control of whiteflies, likely due to their repellant and growth-inhibitory effects. In contrast, untreated plots (T_9) consistently exhibited the highest whitefly populations, underscoring the necessity of active pest management interventions. These findings are consistent with earlier reports that emphasize the efficacy of systemic insecticides against whiteflies in tomato cultivation. [45] Investigated whitefly infestation in tomato, and got the same result in their investigation.

Fruit borer infestation was significantly reduced in plots treated with T_6, as evidenced by the lowest infested fruit count and percent infestation across early, mid, and late fruiting stages. T_6 also achieved the highest reduction in infestation percentages (ranging from 65.96% to 77.30%) and recorded the highest healthy fruit numbers and weights. These results align with previous studies that demonstrated the effectiveness of integrated approaches combining chemical and cultural practices in minimizing fruit borer damage [46-48]. Treatments T_8, T_2, and T_5 also showed considerable efficacy but were slightly less effective than T_6, potentially due to variations in application methods or support structures.

The number of fruits per plot, healthy fruit counts, and overall yield were significantly enhanced in T_6 and T_8 treatments. T_6 recorded the highest yield (9.71 kg/plot or 32.36 ton/ha), which was statistically similar to T_8 (9.02 kg/plot or 30.08 ton/ha), underscoring the potential of Marshal 20EC in maximizing productivity. The untreated control (T_9) exhibited the lowest yield, highlighting the adverse impact of unmanaged pest infestations. The positive correlations observed between fruit weight, fruit number, and yield further reinforce the importance of effective pest management in optimizing tomato production. These results align with the investigation of [13,49].

The significant negative correlation between fruit infestation and yield across fruiting stages emphasizes the critical role of pest management in sustaining productivity. Regression analyses demonstrated that higher levels of infestation consistently led to yield reductions, with the steepest decline occurring at the late fruiting stage. Conversely, the strong positive correlations between fruit weight, number of fruits per plot, and yield underscore the importance of enhancing fruit health and size through effective IPM practices, and [50,51] claimed the same result in their studies.

The results highlight the importance of integrating systemic insecticides like Marshal 20EC with cultural practices such as vertical support to achieve effective pest control and improved yield. Neem oil treatments, while moderately effective, offer an eco-friendly alternative for pest management. However, the relatively lower efficacy of neem oil compared to synthetic insecticides suggests that it may be more suitable as a component of an integrated strategy rather than a standalone treatment. [52,53] investigated and their result aligned with our studies.

The study revealed significant relationships among parameters, confirmed using Pearson's correlation method, indicating robust interactions across treatments. PCA highlighted the dominance of PC1, which accounted for 94.6% of the total variance, with PC2 contributing 4.7%. Treatments 6 and 8, aligned with variables like FWHLF, FNHEF, and FT, emerged as the most impactful, while treatment 9 showed weaker contributions [22,54-56]. Cluster analysis, with a high Ward's coefficient (0.892), identified three distinct groups, further validating the superior performance of treatments 6 and 8. These findings underscore the importance of PC1 and critical variables in driving significant results, guiding future research and optimization strategies.

5. Conclusions

The study demonstrated that integrated pest management (IPM) practices significantly reduced pest infestations and improved tomato yield compared to untreated control. Among the treatments, the application of Marshal 20EC @ 4 ml/L of water with horizontal support (T_6) proved to be the most effective, yielding the lowest pest infestation rates and the highest yield (34.36 t/ha). Treatments involving Neem oil with vertical or horizontal support also performed well, suggesting their potential for organic tomato production. The findings highlight the importance of combining chemical and mechanical methods in IPM strategies to optimize pest control while minimizing yield losses. For broader applicability, further research across different agro-ecological zones and with expanded mechanical and botanical treatments is recommended to develop sustainable and region-specific IPM practices for tomato cultivation.

Authorship Contribution Statement: Md. Tamjidul Haque: Writing – review & editing: Writing – original draft, Investigation, Methodology, Data collection, Conceptualization; Nayan Chandra Howlader: Conceptualization, Writing – original draft, review & editing, Investigation, Methodology, Formal analysis. Visualization; Md. Hasan Miah: Writing—reviewing, and editing, Investigation, Methodology, Formal analysis. Tusar Kanti Roy: Conceptualization, Investigation Writing-original draft, Investigation, Methodology, Writing—reviewing and editing, Supervision, Resources; Uttam Biswas Antu: writing-editing, Validation; Tamim Hasan,: Writing – review & editing, Validation, Conceptualization, Writing-review, Validation. Khairul Alam Bhuiyan Hamim: Writing – original draft, Investigation, Methodology, Formal analysis, Conceptualization; Md. Saiful Islam Shumon: Writing – review, Supervision, Resources, Validation; Md. Jony Ali: original draft, Investigation, Methodology; Sagar Ahmed: Writing – original draft, Investigation, Methodology; Gobinda Roy, Formal analysis, Conceptualization. Subrina Akther: Original draft, Investigation, Methodology; Habiba Yasmin Lutfa: Original draft, Investigation, Methodology.

Data Availability: All data obtained and analyzed during this study are available from the corresponding author upon reasonable request.

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Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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