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RESEARCH ARTICLE

Influence of weather factors on leaf gall thrips and scale infestation in black pepper

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Abstract

This study investigates the relationship between weather factors and the infestation levels of leaf gall thrips (*Liothrips karnyi*) and scales (*Aspidiotus destructor*) in black pepper (*Piper nigrum L.*). These 2 pests that significantly impact pepper production and quality. We analyzed data collected over multiple seasons, to assess how temperature, humidity, rainfall and other climatic variables influence pest prevalence and damage levels. The results reveal that weather factors influence pest damage in black pepper. For leaf gall thrips (%LDT), minimum (r = 0.298*) and maximum temperature (r = 0.771**) showed positive correlations, while maximum humidity (r = - 0.364**), minimum humidity (r = - 0.511**) and rainfall (r = - 0.605**) had negative correlations. Regression models revealed maximum temperature, minimum humidity and rainfall as key predictors, explaining 72.6% of % LDT variation. For scales (%SDS), maximum temperature (r = 0.638**) positively correlated, while rainfall (r = - 0.604**) and humidity negatively correlated. Regression identified maximum temperature, rainfall and minimum temperature as significant, explaining 60.6% of %SDS variability. Maximum temperature consistently increased pest damage, while higher humidity and rainfall reduced it. Our findings suggest that optimal management of these pests requires tailored strategies based on seasonal weather patterns. The outcomes provide valuable insights for farmers, agronomists and policymakers, emphasizing the need for adaptive pest management strategies to counteract climate variability's potential impacts on black pepper's pest dynamics.

Keywords: correlation; leaf gall thrips; regression; relative humidity; scales; temperature; weather

Introduction

India is known as the "spice bowl" of the world because of its incredible variety and abundance of spices, which attracted foreign traders long ago. Black pepper (*Piper nigrum* L.), from the Piperaceae family is regarded as the 'King of Spices,' is derived from dried berries and serves as a significant condiment in international trade for India and other producing countries (1). Black pepper is cultivated in more than 26 countries, including Vietnam, Indonesia, Brazil, Malaysia and Sri Lanka, which are an important producer (2). It is also an important foreign exchange earner for the country. Indian black pepper holds a preeminent position in the global market due to its inherent qualities. India served as a prominent producer, exporter and consumer of black pepper until 1990s, when Vietnam emerged as the largest producer. In India, the area cultivated with pepper in crop year 2020 exceeded 259148 ha, yielding 104071 tons and attaining a productivity of 402 kg/ha. The major cropped area is in India (259148 ha), followed by Indonesia (116375 ha), Vietnam (113142 ha), Brazil (27850 ha) and Malaysia (17437 ha), with respective production of 104071, 78000, 250000, 78000 and 24000 tons in 2020 (3). Among various factors responsible for low productivity, infestation by insect pests has been identified as a major one. Thirty-four insect pests were reported to be infesting black pepper in India. Among them, the major ones are the pollu beetle (*Longitarsus nigripennis* Auctt), marginal gall thrips (*Liothrips karnyi* Bagnall) and top shoot borer (*Scirpophaga novella* Fabricius). The Pollu beetle (*Longitarsus nigripennis*, Chrysomelidae: Coleoptera) is a bluish-yellow, shiny flea beetle. Eggs are laid on pepper berries, with 1 - 2 eggs per hole and the egg stage lasts 5-8 days. The grubs feed inside the berries, hollowing them out ("Pollu") and causing them to crumble. The larval stage lasts 30 - 32 days, after which pupation occurs 5 - 7.5 cm deep in the soil for 6 - 7 days. The complete life cycle spans 40 - 50 days, with 4 overlapping generations occurring annually, The marginal gall thrips, *Liothrips karnyi* (Thysanoptera: Thripidae), primarily affects pepper plants in India. Eggs are laid singly in marginal leaf folds or on the leaf surface, with an egg period of 6 - 8 days. Whitish, sluggish nymphs feed on leaves, causing marginal galls; their development lasts 9 - 13 days. Pupation occurs for 2 - 3 days and adults live for 7 - 9 days. This pest stunts plant growth and hampers spike formation in severe infestations and The top shoot borer, *Cydia hemidoxa* (Eucosmidae: Lepidoptera), affects pepper plants in India. The greyish-green larvae, 12 - 14 mm long, feed on young leaves, causing terminal shoot damage. The larval period lasts 10 - 15 days, followed by pupation inside the shoots for 8 - 10 days. The adult moth has black forewings with red distal halves and greyish hindwings. The life cycle completes in about a month. Leaf feeders and sap feeders like scales and mealy bugs were grouped as minor pests (4). Four species of significance include the 'pollu' beetle, top shoot borer, leaf gall thrips, along with scale insects. Infestation by thrips resulted in formation of marginal galls (5). The morphology of galls induced by thrips on a wide variety of trees and plants in India including *L. karnyi* on black pepper was studied prviously (6). According to a study, the feeding activity of thrips caused infested leaves to thicken and crinkle, as well as increase in size and form marginal galls (7). Another study reported that *L. karnyi* was only pest-infesting pepper in South Wayanad (8). Cultivar, Kalluvally was least susceptible to attack by pest, while most susceptible was Panniyur 1. Leaves on the middle portion of vines were preferred as food. Infestation due to leaf gall thrips ranged from 25 - 75% in Idukki district, according to Kerala Agricultural University (9). A variety of insecticides have been assessed and endorsed for significant insect pests. However, the indiscriminate application of broad-spectrum insecticides has resulted in the emergence of insect resistance to natural predators. These insecticides are comparatively toxic to mammals, including humans, and highly lethal to fish (10, 11). Seventeen predators and 4 parasitoids targeting scale insects that infest black pepper include *Pseudoscymnus* sp., *Aphytis* sp., and *Chilocorus circumdatus* (12).

Various “species of scale insects viz., *Lepidosaphes piperis, Aspidiotus destructor,* and *Lecanium marsupial* recorded on black pepper in India, among them mussel scale (*Lepidosaphes piperis* Gr.) is an important pest especially at higher altitudes in field and on older cuttings in nursery (13, 14). Infestation appears as encrustations primarily on leaves and stems, intensifying during summer. They extract plant sap, leading to yellowing and desiccation of affected plant regions. Pest management strategies predominantly depend on synthetic pesticides. For several years, researchers globally have been determined to identify effective, economical, acceptable, and sustainable pest control measures, particularly for black pepper insect pests (13). Scale” insects, including mussel scale (*Lepidosaphes piperis*) and coconut scale (*Aspidiotus destructor*), are emerging as significant pests of black pepper at elevated altitudes due to changing climatic conditions (12).

Materials and Methods

An experiment was performed in the field at the Horticultural Research Station, Yercaud, Salem, Tamil Nadu, utilizing the most prominent black pepper variety, Panniyur 1, for 2 years (2021 - 22 and 2022 - 23). Yercaud is located in the Eastern Ghats of Tamil Nadu at an elevation of 1500 m above MSL. The research station is located at 11°79’63.85” N Latitude and 78° 21’16.01” E Longitude. Four seasons are observed here: winter, summer, monsoon and post-monsoon. April-May is the warmest month of the year, with the highest mean maximum temperature (30.3 °C), while December is the coldest month with the lowest mean minimum temperature (16 °C). Average annual rainfall ranges from 1300 mm - 1600 mm.

The soils in the area are acidic with low organic carbon and low phosphorous and potassium content. In study site, the crop was kept free from the insecticidal application along with all other recommended cultural practices of application of 10 kg of composted cattle manure per vine before the onset of the South-West monsoon followed by 50% of the recommended inorganic N, 10 kg FYM, 50 g *Azospirillum*, 50 g Phosphobacteria, and 200 g vesicular arbuscular mycorrhiza (VAM) per vine followed during the research period. Weekly observations of leaf gall thrips and scales-infested vines were conducted during a 2-year period.

Twenty-five vines infested with leaf gall thrips and scales were selected by using a random sampling method from the field. Observations were conducted on tagged vines at weekly intervals. Number of leaf gall thrips populations on 25 leaves per vine with damage symptoms was recorded. The number of spikes affected by scale insects out of 25 spikes per vine and the number of vines showing symptoms of scale insect infestation out of 25 vines were recorded.

Data on abiotic factors, such as meteorological parameters (e.g., RH, maximum and minimum temperature and rainfall) were recorded during the experiment period from the agro-meteorological observatory installed at Horticultural Research Station, Yercaud. Weekly data on incidence of leaf gall thrips and scales over 2 years was collected from HRS, Yercaud on black pepper.

Statistical analysis

Correlation coefficient

The correlation coefficient measures the strength of the linear relationship between variables X and Y.

It was calculated by employing the following formula,

$$r = \frac{n\Sigma\ XiYi - \Sigma\ XiYi}{\sqrt{n\Sigma\ Xi - (\Sigma XI)2(n\Sigma Yi2 - \Sigma Yi)2}} \quad \text{(Eqn. 1)}$$

Testing correlation coefficient: The significance of correlation coefficient (r) was tested employing a t-test.

Hypothesis was set as

H0: $\rho = 0$

H1: $\rho \neq 0$

Test statistic was calculated as follows

$$t = \frac{|r - 0|}{\sqrt{\frac{1-r^2}{n-2}}} \quad \text{(Eqn. 2)}$$

Where, r- sample correlation coefficient

n- sample size

Comparison of calculated t-value with critical t-value for (n-2) degrees of freedom to derive significant inferences.

Simple regression analysis

Data concerning insect pests were examined through simple linear regression, with insect pest eggs and dead heart damage as dependent variables and weather parameters and sowing date as independent variables.

The simple linear regression model was

$$Y = \alpha + \beta X + \varepsilon \quad \text{(Eqn. 3)}$$

Where, Y-Dependent Variable.

X-Independent variable.

α-intercept

β-slope of regression line

ε-random error

$\hat{a}$ & $\hat{b}$ estimates of α & β.

Where,

$$\hat{b} = \frac{n\Sigma XiYi - \Sigma Xi \Sigma Yi}{n\Sigma Xi2 - (\Sigma Xi)2} \qquad \hat{a} = Y - bX \quad \text{(Eqn. 4)}$$

Significance of regression coefficient. regression coefficient significance evaluated by employing F-statistic

$$F = \frac{\text{Regression mean sum of squares (n - 2)}}{\text{Error mean sum of Squares}}$$

Where,

$$\text{Regression SS} = b\left(\Sigma XiYi - \frac{\Sigma Xi \Sigma Yi}{n}\right)$$

Error sum of squares =

$$(\Sigma\,(Yi - Y)2 - b\,[\Sigma XiYi] - \frac{\Sigma XiYi}{n} \quad \text{(Eqn. 5)}$$

Coefficient of determination (R2)

Coefficient of determination (R2) applied to measure the variation of a fitted model.

$$R^2\,(\%) = \frac{\text{Sum of square due to regression}}{\text{Total sum of squares}}$$

$$= \frac{b\,\Sigma\,(Xi - X)\,(Yi - Y)}{\Sigma\,(Yi - Y)^2} \quad \text{(Eqn. 6)}$$

Multiple regression model

A multiple linear regression model is applicable when multiple variables elucidate the dependent variable. Model is presented here,

$$Y = \alpha + ß1X1 + ß2X2 + \text{-----} + ß\rho\, X\rho + \varepsilon \quad \text{(Eqn. 7)}$$

Where,

Y dependent variable

Xi - independent variables

ßi - partial regression coefficients of Y on Xi where I=1,2…P.

In the current research, Y was taken as the incidence of pests and Xi weather parameters *viz.,* rainfall, temperature and RH. For this mode, coefficient estimates(βi's and α) will be determined using the least squares method.

Results

Leaf gall thrips, *Liothrips karnyni*

The incidence of leaf gall thrips was recorded as the percentage of leaves damaged (Table 1) The highest percentage of leaf damage was reported during the 18th standard week of 2022 (23.90%), followed by the 17th, 20th, and 19th standard weeks of 2022 with the mean percentage of leaves damaged being 23.80, 23.70 and 23.60% correspondingly. Conversely, the least damage of leaves was recorded during the 36th standard week of 2021 (8.00%) followed by the 37th (8.20%), 38th (8.40%) and 39th (8.40%) standard weeks of 2021 (Fig. 1, Fig. 2 and Fig. 3(a)).

Scale insects, *Aspidiotus destructor*

Scale insects on spikes were absent from 36th - 39th standard weeks of 2021 (Table 1). However, the population began to build up from the 40th standard week of 2021 and reached maximum spikes during the 18th standard week of 2022. The percentage of spikes damaged by scales peaked at 10.80% during the 18th standard week of 2022, followed, by the 17th and 19th standard weeks of 2022, with a mean percentage of spikes damaged by scales being 10.60% and 10.60%, correspondingly. Least damage on spikes was recorded during 36th to 39th standard weeks of 2021 (0.00) followed by the 40th standard week of 2021 (4.10%) (Fig. 1, Fig. 2 and Fig. 3(b)).

Percentage of vines damaged by scales insets

The percentage of vines infested by scales was maximum (30.30) during the 18th standard week of 2022 (Table 1). Scale infested 12 - 30.30% of vines over 1 year from the 36th standard week of 2020 to the 35th standard week of 2021. The lowest percentage of vines infested by scales was recorded during the 40th standard week of 2021 (Fig. 1, Fig. 2 and Fig. 3(c)).

Intensity of vines damaged by scale insects

The intensity of vines damage by scale insects increased from the 49th standard week of 2021 to the 32nd standard week of 2022 (Table 1, Fig. 3 (c)).

Table 1. Seasonal incidence of thrips and scales in black pepper

Standard week (2021 - 22)	Minimum Temperature	Maximum Temperature	Minimum Humidity	Maximum Humidity	Rainfall	% LDT	% SDS	% VDS
36	15.57	22.71	75.57	97.43	120.00	8.00	0.00	0.00
37	18.86	23.29	75.00	97.14	60.00	8.20	0.00	0.00
38	20.50	24.71	70.86	95.43	0.00	8.35	0.00	0.00
39	22.07	24.79	71.00	94.29	69.00	8.40	0.00	0.00
40	21.14	24.14	65.43	93.71	43.00	9.80	4.10	12.00
41	19.93	24.21	68.29	96.86	35.00	9.85	4.20	12.00
42	19.43	23.07	71.00	96.29	55.00	9.90	4.50	12.60
43	20.79	23.29	68.29	96.14	17.00	10.20	4.70	13.80
44	20.07	23.07	70.43	96.14	0.00	10.80	5.10	18.60
45	19.57	23.43	73.29	96.14	24.00	11.20	5.30	19.20
46	18.93	22.93	74.71	97.00	30.00	11.20	5.40	18.60
47	18.21	23.93	75.71	98.00	0.00	15.30	5.20	24.60
48	18.86	24.07	73.71	96.71	43.00	15.10	5.90	24.00
49	19.21	23.00	70.00	96.00	70.00	15.90	5.60	25.20
50	20.07	23.79	67.86	97.29	2.00	15.60	6.30	25.80
51	17.57	23.36	59.43	96.43	21.00	17.10	6.40	27.60
52	19.29	24.29	52.29	96.43	0.00	17.80	6.70	27.65
1	15.57	23.50	53.86	96.29	44.00	17.90	8.10	27.90
2	18.14	22.86	65.14	97.29	24.00	17.95	8.20	28.05
3	19.71	25.14	67.14	94.86	6.00	18.10	8.40	28.15
4	16.86	23.29	66.14	94.29	0.00	18.30	8.40	28.30
5	16.00	25.71	64.29	91.14	0.00	18.45	8.60	28.65
6	19.14	25.36	58.57	95.29	0.00	19.10	8.65	28.90
7	16.07	23.86	56.86	94.29	0.00	19.40	8.80	28.90
8	16.57	24.57	58.43	95.86	0.00	19.45	8.95	28.95
9	20.36	30.00	56.43	96.57	0.00	19.60	9.00	29.00
10	17.50	31.57	58.29	95.29	0.00	20.30	9.20	29.15
11	14.43	30.36	51.71	93.71	0.00	20.60	9.40	29.15
12	17.07	31.29	58.57	94.86	0.00	20.70	9.65	29.25
13	18.00	33.14	54.57	94.86	0.00	20.85	9.90	29.30
14	18.71	28.21	57.29	95.29	3.00	22.60	10.10	39.35
15	18.00	31.71	61.14	96.43	37.00	22.80	10.25	29.55
16	20.50	28.79	63.14	95.57	21.00	23.50	10.30	29.70
17	21.86	31.50	64.57	97.14	0.00	23.80	10.60	30.20
18	23.57	33.79	70.43	94.29	0.00	23.90	10.80	30.30
19	25.36	36.71	73.86	95.86	0.00	23.60	10.60	30.10
20	26.21	37.50	66.43	93.57	0.00	23.70	10.40	30.00
21	25.50	36.79	66.43	94.29	0.00	23.50	9.20	29.50
22	24.07	34.07	63.29	222.29	0.00	23.00	9.10	29.20
23	23.14	33.71	60.43	96.14	0.00	22.80	8.90	29.00
24	22.71	32.43	54.00	91.71	0.00	22.60	8.60	28.60
25	22.21	32.21	52.00	93.71	0.00	22.40	8.20	28.10
26	21.86	32.00	52.29	94.14	0.00	22.00	8.10	27.20
27	21.57	29.64	60.29	94.86	0.00	21.60	8.00	26.30
28	21.21	29.07	54.29	95.14	0.00	21.10	7.90	26.20
29	21.14	28.57	53.43	96.29	0.00	20.20	7.60	26.00
30	20.64	28.36	53.29	94.29	0.00	19.80	7.50	25.90
31	20.29	28.21	52.29	95.29	0.00	19.60	7.30	25.40
32	20.21	27.93	52.14	95.57	0.00	19.00	6.20	25.30
33	19.79	27.50	51.86	95.71	0.00	16.20	5.20	21.20
34	19.64	27.29	52.29	96.14	0.00	15.70	5.10	20.20
35	18.79	26.93	53.14	96.29	0.00	14.20	4.60	18.30

Observations of sucking pests and their damage were taken from vines grown in different block of the farm

% LDT - Percent Leaf Damage by Thrips ,% SDS - Percent Spikes Damaged by Scales, % VDS - Percent Vines Damaged by Scales

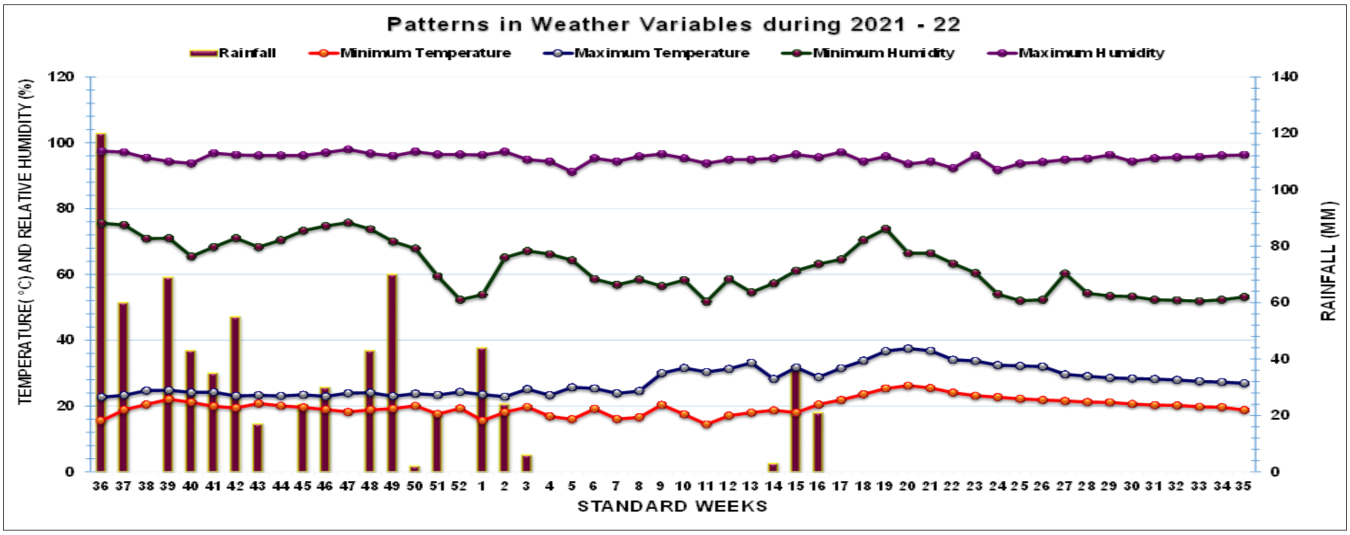

Fig. 1. Patterns in the weather variables during 2021 - 22.

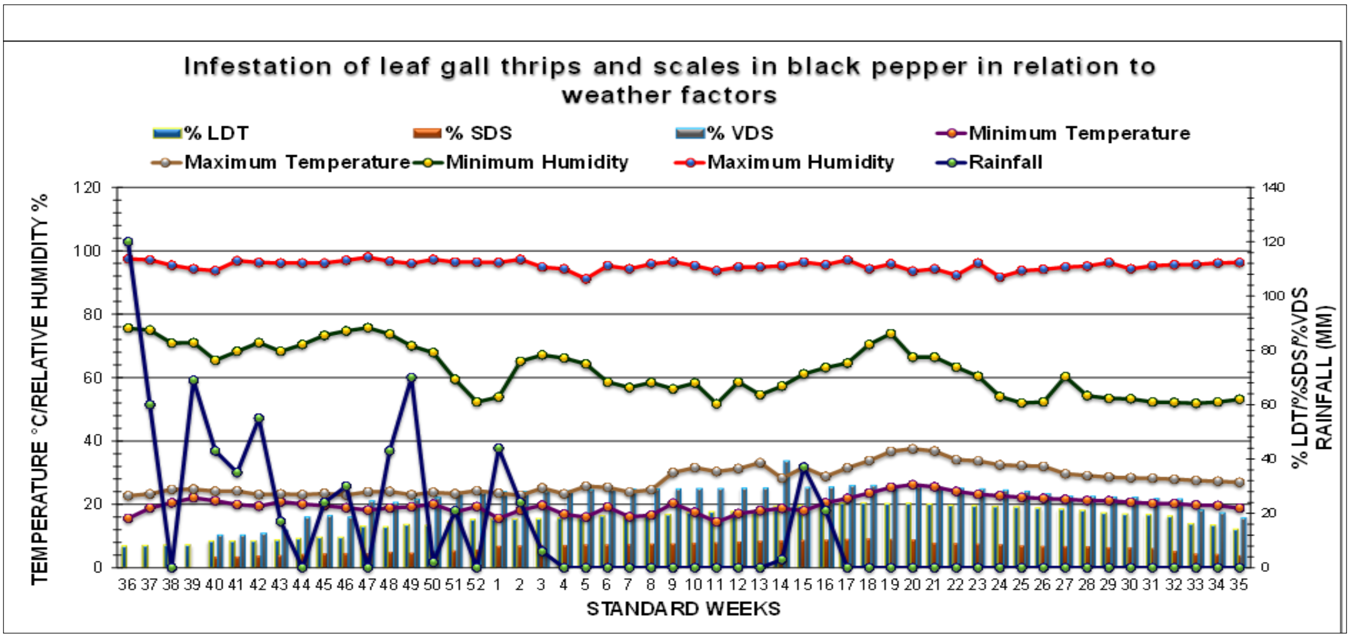

Fig. 2. Population dynamics of leaf gall thrips, scales in relation to weather factors.

Correlation and regression among weather parameters against % leaf damaged by leaf gall thrips

Simple correlation studies

Pearson's correlation coefficient (ρ) is used as a metric for selecting appropriate input features and presents heat maps that reflect ρ-values within 5 selected weather features, namely minimum temperature (°C), maximum temperature (°C), minimum humidity (%), maximum humidity (%) and rainfall (mm), with percent leaf damaged by thrips (% LDT) in black pepper. A strong positive correlation of ρ = 1 is indicated by dark brown, whereas a strong negative correlation ρ = -1 is indicated by light blue in the heat map (Fig. 4).

For percent leaf damaged by thrips (% LDT) (Table 2) that is influenced by weather factors *viz.,* minimum

Table 2. Correlation coefficients between the incidence of thrips, scales and their damage on black pepper and weather parameters

Weather parameters/Insect population and natural enemies			Temperature °C		Relative humidity %		Total Rainfall (mm)	R^2	Regression Equation
			Max. Temp	Min. Temp	Max. Humid	Min. Humid			
2021 - 22	LDT	R^2	0.594	0.887	0.151	0.261	0.365	0.726	LDT = -0.158 - (0.686 x Maximum Temperature) - (0.264 x Minimum Temperature) + (0.040 x Maximum Humidity) - (0.212 x Maximum Humidity) - (0.331 x Rainfall)
		r	0.771**	0.298*	-0.364**	-0.511**	-0.605**		
2021 - 22	SDS	R^2	0.406	0.024	0.113	0.165	0.364	0.606	% SDS = 1.955 + (0.594 x Maximum Temperature) - (0.399 x Minimum Temperature) + (0.001 x Maximum Humidity) - (0.065 x Maximum Humi) - (0.443 x Rainfall)
		r	0.638**	0.156	-0.324*	-0.407**	-0.604**		
2021 - 22	VDS	R^2	0.247	0.004	0.06	0.226	0.399	0.534	VDS = -10.088 + (0.421 x Maximum Temperature) - (0.326 x Minimum Temperature) + (0.077 x Maximum Humidity) - (0.077 x Maximum Humidity) - (0.476 x Rainfall)
		r	0.498**	0.067	-0.249	-0.475**	-0.632**		

* Significant at p = 0.05; ** Significant at p = 0.01

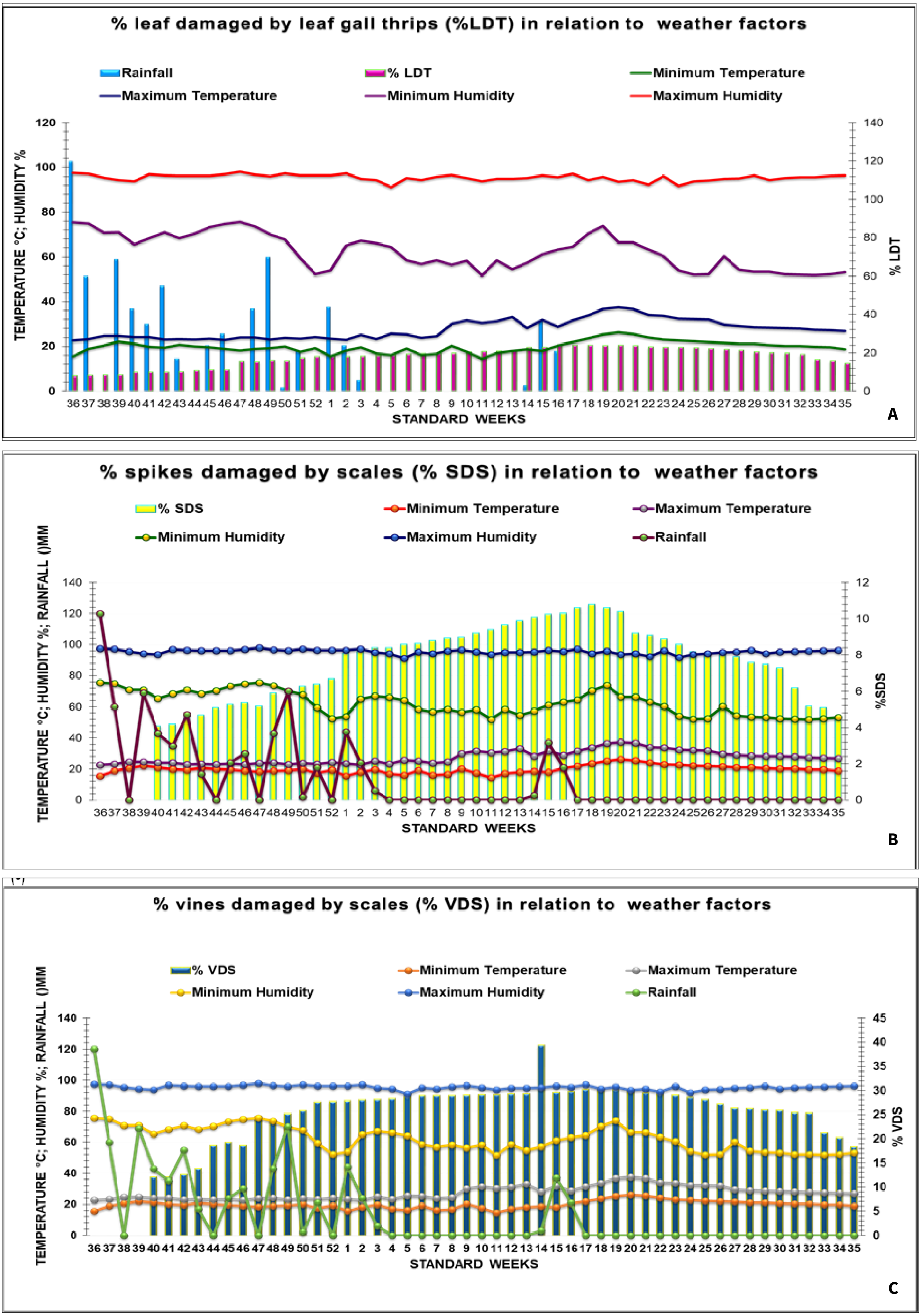

Fig. 3. Infestation level of leaf gall thrips and scales in relation to weather factors in black pepper (a) % vines damaged by scales (b) % leaf damaged by thrips (c) % spikes damaged by scales.

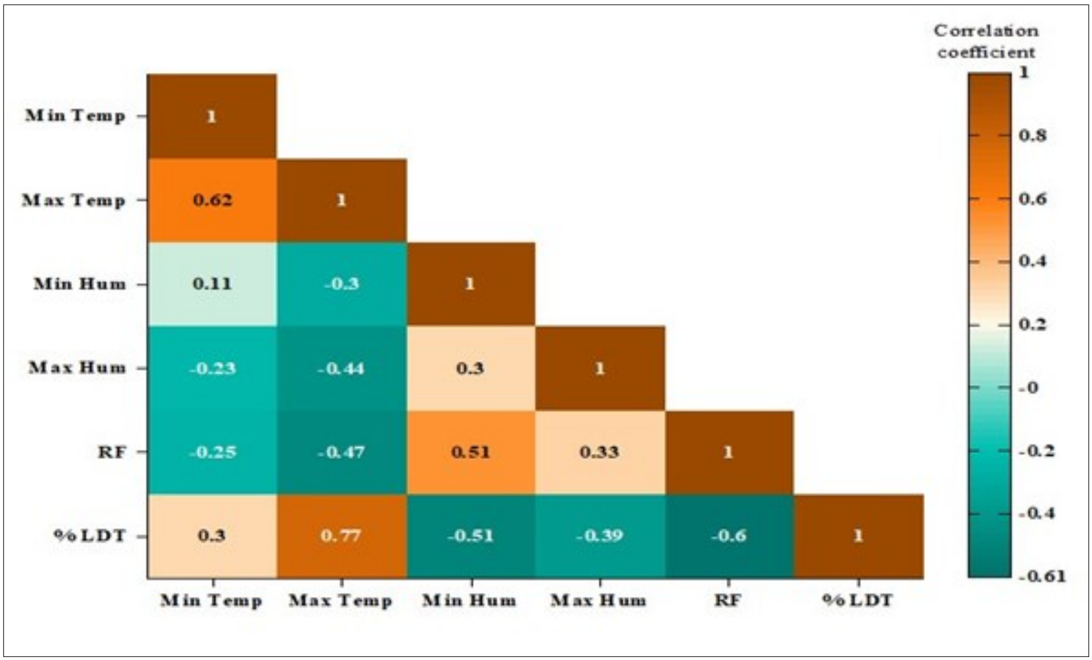

Fig. 4. Heat map correlation (Pearson correlation) on the influence of weather factors with % leaves damaged by thrips (% LDT) and the results of the correlation analysis has been scaled by a color gradient that goes from dark brown (positive correlation) to light blue (negative correlation) by increasing color density, significant correlation coefficients at $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$.

temperature, maximum temperature, minimum humidity, maximum humidity and rainfall, % LDT demonstrated a significant positive correlation with minimum temperature r = 0.298*. Besides minimum temperature and maximum temperature was second important weather factor that demonstrated significant positive correlation with percent leaf damaged by thrips (r = 0.771**). Significant negative correlation coefficient, describing lesser damage between thrips (% LDT) and maximum humidity (r = -0.364**), minimum humidity (r = - 0.511**) and rainfall (r = - 0.605**).

Linear regression studies

Regression coefficient (b) and constant (a) (Fig. 5) were calculated to establish regression equations (Table 3 and Table 4) revealing that correlation between % LDT and maximum temperature, minimum temperature demonstrated significant positive impact, while maximum RH, minimum humidity and rainfall illustrated a significant negative impact.

Multiple linear regression studies

Re-run indicates an R-Squared value 0.771 for maximum temperature. This indicates that a model comprising solely these 3 variables significantly accounts for variations in % LDT. Analysis of individual t-values indicates that maximum temperature is most significant independent variable impacting % LDT, followed by minimum humidity as well as rainfall (Table 5a). Multiple regression (MR) coefficients for various meteorological parameters calculated (Table 5). MR equation incorporating weather parameters to predict % leaf damage caused by leaf gall thrips is as follows:

% LDT = -0.158 - (0.686 x Maximum Temperature) - (0.264 x Minimum Temperature) + (0.040 x Maximum Humidity) - (0.212 x Minimum Humidity) - (0.331 x Rainfall)

Determination coefficient (R^2) 72.6%, indicating significance of these parameters affecting the percentage of % LDT in black pepper. This equation suggests that each unit increase in maximum humidity elevate % LDT by up to 0.040%. Conversely, a 1-unit increase in maximum temperature, minimum temperature, minimum humidity and rainfall resulted in a decrease of % LDT by 0.686, 0.264, 0.212 and 0.331 correspondingly. Results indicated that linear regression analysis utilized multiple parameters affecting % LDT as a dependent variable, with weather conditions as an independent variable. Weather-based linear regression model accounted for 72.6% of the variance in % LDT fluctuation and variation.

Correlation and regression among weather parameters against % spikes damaged by scales (SDS)

Simple correlation studies

Pearson correlation coefficient ρ as a metric for selecting appropriate input features (Fig. 6), represent heat maps that reflect ρ-values in five selected weather features, termed as minimum temperature, maximum temperature, minimum humidity (%), maximum humidity (%) and rainfall (mm), with SDS in black pepper. The heat map indicates a strong positive correlation (ρ = 1) in green and strong negative correlations (ρ = - 1) in red. For (% SDS, that is influenced by weather factors *viz.,* minimum temperature, maximum temperature, minimum humidity, maximum humidity and rainfall. % SDS (Table 2) displayed a significant positive correlation with maximum temperature r = 0.638**. Besides maximum temperature, the minimum temperature was second important weather factor that displayed a non-significant positive correlation with % spikes damaged by scales (r = 0.156). Significant negative correlation coefficient, describing lesser damage between scales (% SDS) and rainfall (r = - 0.604**), maximum humidity (r = - 0.324*) and minimum humidity (r = - 0.407**).

Linear regression studies

Regression coefficient (b) and constant (a) (Fig. 7) calculated to establish regression equations (Table 3 and Table 4) revealing correlation between % SDS and maximum

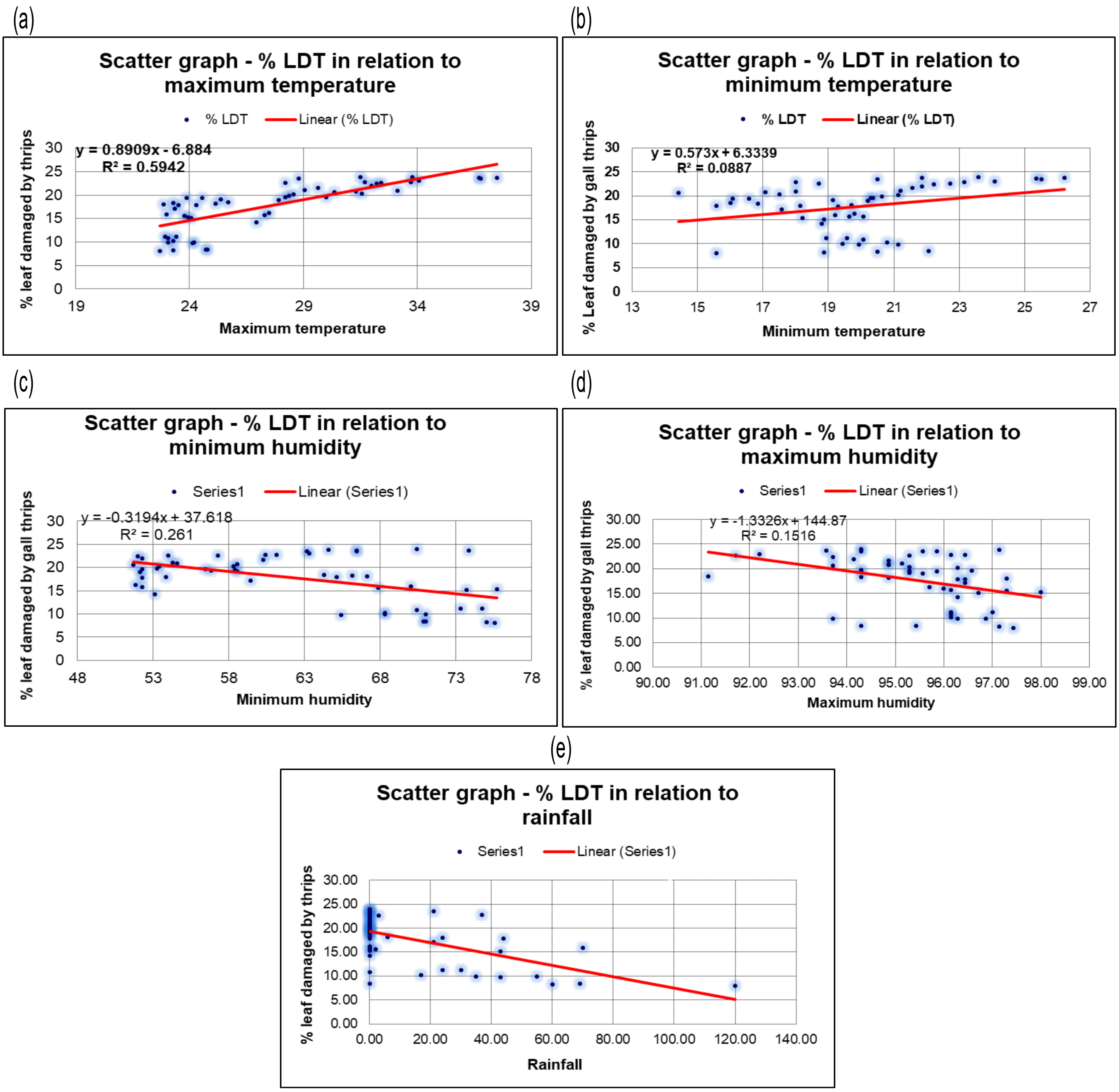

Fig. 5. Scatter graph of % leaf damage by thrips (% LDT) in relation to weather factors (a) Minimum temperature (b) Maximum temperature (c) Minimum humidity (d) Maximum humidity (e) Rainfall.

Table 3. Regression model developed for leaf gall thrips and scales infestation on black pepper

Insect pest infestation	Max. Temp (°c) (X1)	Min. Temp (°c) (X2)	Max. RH (%) (X3)	Min. RH (%) (X4)	Rainfall (mm) (X5)
% LDT	Y = 0.8909 x – 6.884	Y = 0.573 x + 6.333	Y = - 1.332 x + 144.87	Y= -0.319 x + 37.618	Y = -0.1189 x + 19.367
% SDS	Y = 0.420 X – 4.521	Y = 0.1716 X + 3.693	Y = - 0.659 X + 69.999	Y = - 0.145 X + 16.157	Y = - 0.067 X + 8.044
% VDS	Y = 1.017 X – 4.225	Y = 0.227 X + 19.349	Y = -1.589 X + 175.50	Y = -0.525 X + 56.634	Y = - 0.22X + 26.926

Table 4. Correlation and linear regression coefficients between leaf gall thrips, scales and weather factors on black pepper

Weather parameters	% Leaf damaged by leaf gall thrips			% Spikes damaged by scales			% Vines damaged by scales		
	r	b	a	r	b	a	r	b	a
Max. Temp (°c)	0.771**	0.890	-6.884	0.638**	0.420	-4.521	0.498**	1.017	-4.225
Min. Temp (°c)	0.298*	0.573	6.333	0.156	0.176	3.693	0.067	0.227	19.349
Max. RH (%)	-0.364**	- 1.332	144.87	-0.324*	-0.659	69.999	-0.249	-1.589	175.500
Min. RH (%)	-0.511**	-0.319	37.618	-0.407**	-0.145	16.157	-0.475**	-0.525	56.634
Rainfall (mm)	-0.605**	-0.118	19.367	-0.604**	-0.067	8.044	-0.632**	-0.22	26.926

* And ** indicate significance of values at P = 0.05 and 0.01, respectively

Table 5. Multiple regression with % LDT and weather parameters

Weather parameters	Partial regression coefficients	Standard error	't' Value	R^2
Intercept	-0.158	30.441	-0.005	
X1 - Maximum Temperature (°c)	0.686	0.135	6.391	
X2 - Minimum Temperature (°c)	-0.264	0.208	-1.859	
X3 - Maximum RH (%)	0.040	0.313	0.270	0.726
X4 - Minimum RH (%)	-0.212	0.063	-1.469	
X5 - Rainfall (mm)	-0.331	0.019	-2.379	

N= 54, *Significant at p=0.05 **Significant at p=0.01, NS- Non Significant, Multiple R- Squared = 0.726, Adjusted R-Square = 0.696, F Statistic = 24.364, on 5, p-value = 0.000, Significant codes = *

Table 5a. Final run of a linear regression model with the 3 most significant Independent variables

Variables	Coefficient	Standard Error	t-value	p-value	Rank of t-value
Maximum Temperature	0.701	0.103	6.799	0.000	1
Minimum Humidity	-0.138	0.057	-2.417	0.019	2
Rainfall	-0.040	0.019	-2.081	0.043	3

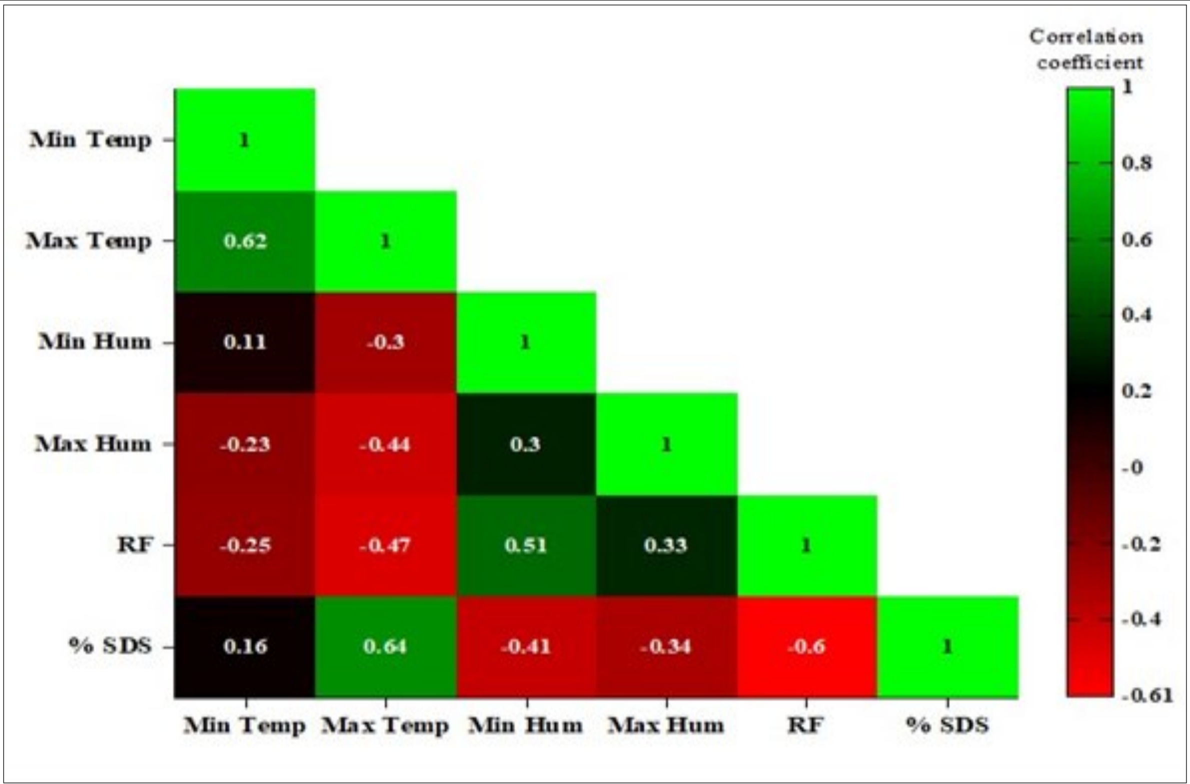

Fig. 6. Heat map correlation (Pearson correlation) on influence of weather factors with % spikes damaged by scales (% SDS) and the results of the correlation analysis have been scaled by a color gradient that goes from green (positive correlation) to dark red (negative correlation) by increasing color density, significant correlation coefficients at p ≤ 0.05, ** p ≤ 0.01, and *** p ≤ 0.001.

temperature demonstrated significant positive impact, while maximum RH, minimum humidity and rainfall displaying a significant negative impact.

Multiple linear regression studies

Initial execution of "multiple linear regression models incorporated all 5 independent variables displayed in (Table 6) concerning the dependent variable, with results from these executions detailed as follows. p-value is approximately zero for an F-statistic 14.150, indicating that the model is significant. This is additionally corroborated by a coefficient of determination, or Multiple R^2 = 0.606. However, according to this model, maximum temperature, rainfall and minimum temperature are the 3 most important variables that affect % SDS. Due to collinearity among independent variables, stepwise exclusion was performed to optimize the model. These results are displayed in Table 6a. Variables of minimum and maximum humidity were eliminated in order to optimize model. Final model consequently encompassed maximum temperature, minimum temperature and rainfall, that had been predominant variables in the initial iteration. Rerun indicates an R^2 value of 0.407 for maximum temperature. This indicates that model comprising exclusively each of these variables significantly accounts for variations in % SDS. Analysis of individual t-values reveals that maximum temperature is the most significant independent variable impacting % SDS, succeeded by rainfall and minimum temperature (Table 6a). Regression coefficients for various meteorological parameters have been determined (Table 6). MR equation incorporating weather parameters for predicting scale-induced damage to spikes is as follows.

Determination coefficient (R^2) 60.6% demonstrating the importance of these parameters influencing % SDS on black pepper. This equation indicates that each unit increase in maximum temperature (Tx) and maximum humidity results in a increase of % SDS by 0.594 and 0.001%,

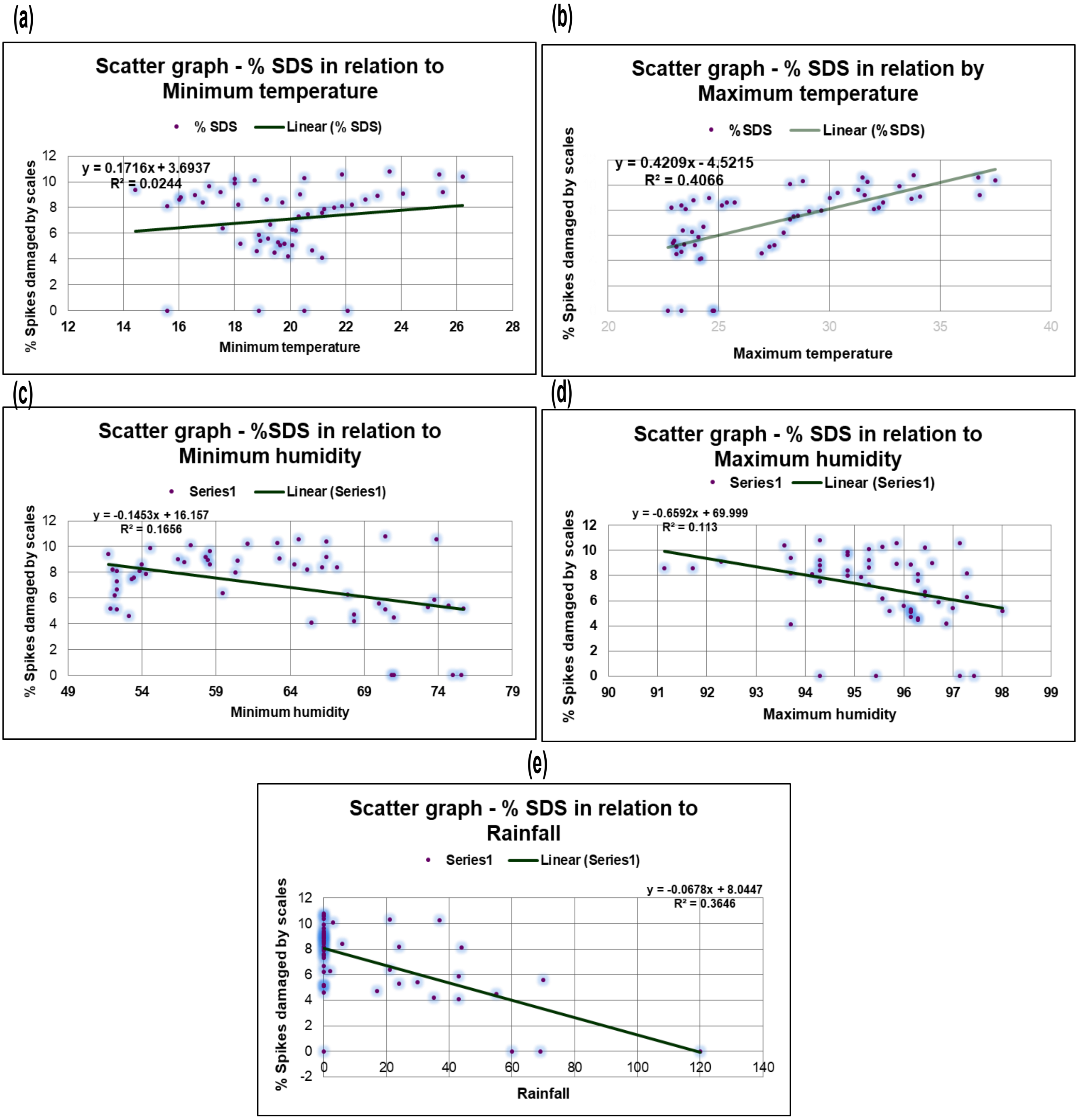

Fig. 7. Scatter graph of % spikes damaged by scales (% SDS) in relation to weather factors (a) Minimum temperature (b) Maximum temperature (c) Minimum humidity (d) Maximum humidity (e) Rainfall.

Table 6. Multiple regression with % SDS and weather parameters

Weather parameters	Partial regression coefficients	Standard error	't' Value	R^2
Intercept	1.955	20.848	0.094	
X1 - Max. Temp (°c)	0.594	0.093	5.004	
X2 - Min. Temp (°c)	-0.399	0.143	-2.950	
X3 - Max. RH (%)	0.001	0.214	0.006	0.606
X4 - Min. RH (%)	0.065	0.043	0.440	
X5 - Rainfall (mm)	-0.443	0.013	-3.353	

N = 54, *Significant at p = 0.05 **Significant at p=0.01, NS- Non Significant ,Multiple R–squared = 0.606, Adjusted R-square = 0.563, F-statistic = 14.150, on 5, p-value = 0.000, Significant codes = *

Table 6a. Final run of linear regression model with the 3 most significant Independent variables

Variables	Coefficient	Standard Error	t-value	p-value	Rank of t-value
Max. Temp	0.421	0.072	5.853	0.000	1
Rainfall	-0.044	0.013	-3.491	0.001	2
Min. Temp	-0.394	0.127	-3.105	0.003	3

SDS = 1.955 + (0.594 x Max Temp) - (0.399 x Min Temp) + (0.001 x Max Humi) - (0.065 x Min Humi) - (0.443 x Rainfall) correspondingly. Conversely, a one-unit increase in minimum temperature (Tn) would result in a decrease of % SDS by 0.399, 0.065 and 0.443 for minimum humidity as well as rainfall, correspondingly. Results indicated that linear regression analysis utilized multiple parameters affecting % SDS as a dependent variable, with weather conditions operating as an independent variable. The weather-based linear regression model accounted for 60.6% of variation in % SDS fluctuation along with variability.

Correlation and regression among weather parameters against % vines damaged by scales (VDS)

Simple correlation studies

Pearson correlation coefficient ρ serves as a criterion for selecting suitable input features. It represents heat maps reflecting ρ-values between 5 selected weather features, namely minimum temperature & maximum temperature (in ° C), minimum and maximum humidity (%) as well as rainfall (mm), with % VDS in black pepper. Heat map (Fig. 8) indicates a strong positive correlation of ρ = 1 in green as well as a strong negative correlation of ρ = -1 in dark orange. For % VDS, which is influenced by weather factors *viz.,* minimum temperature, maximum temperature, minimum humidity, maximum humidity and rainfall, % VDS (Table 2) demonstrated a significant positive correlation with maximum temperature r = 0.498*. Besides maximum temperature, minimum temperature was the second important weather factor that demonstrated a non-significant positive correlation with % VDS (r = 0.067). The significant negative correlation coefficient, describing lesser damage between scales (% VDS) and minimum humidity (r = - 0.475**), rainfall (r = - 0.632**), while non-significant negative correlation observed between % VDS and maximum humidity (r = - 0.249).

Linear regression studies

Pooled regression calculated to establish regression equations (Fig. 9) illustrated correlation amongst % VDS minimum temperature and maximum RH insignificant. Only maximum temperature displayed significant positive and minimum RH, rainfall displayed significant negative impact. Regression equation (Table 3 and Table 4) calculated for maximum temperature (X) and % VDS (Y) was Y = 1.017X - 4.225 that indicated that % VDS increased by 0.498 for every unit increase in maximum temperature whereas the regression equation for minimum RH; Y = -0.525X + 56.634 & for rainfall, Y = -0.22X + 26.926 that revealed every unit increase in minimum RH, rainfall % SDS decreased by 0.475 and 0.632 correspondingly.

Multiple linear regression studies

The initial "run of the multiple linear regression models comprised all 5 independent variables specified in (Table 7), in relation to the dependent variable. The p-value is effectively zero for an F-statistic of 10.497, indicating that the model is significant. This is additionally corroborated by a coefficient of determination, or Multiple R^2 of 0.534. The 3 most significant variables influencing % VDS according to this model are rainfall, maximum temperature and minimum temperature. The results may vary with the stepwise exclusion of certain variables, requiring a rerun due to collinearity and interdependence among some independent variables (Table 7a) illustrates these results. The" variables removed to optimize the model are minimum and maximum humidity. The final model incorporated maximum temperature, minimum temperature and rainfall, as these variables were the most influential in the initial analysis. The rerun indicates an R^2 value of 0.632 for rainfall. This indicates that a model

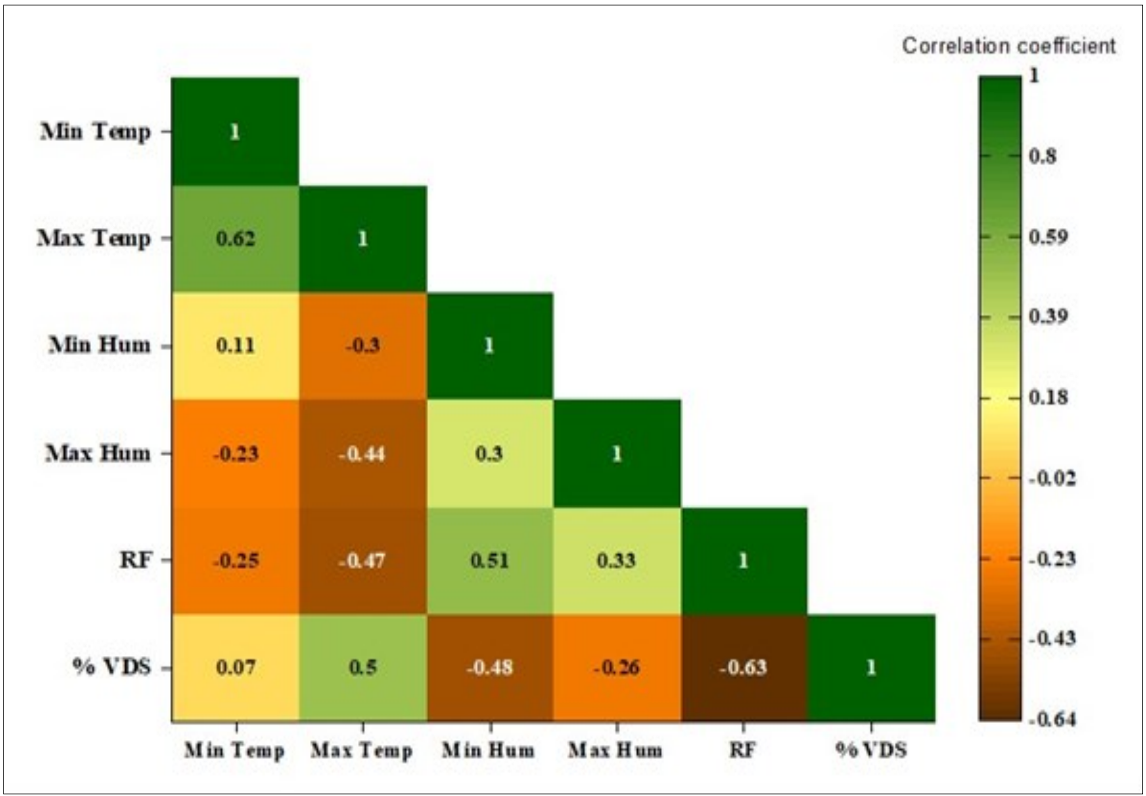

Fig. 8. Heat map correlation (Pearson correlation) on the influence of weather factors with % vines damaged by scales (% VDS) and the results of the correlation analysis has been scaled by a color gradient that goes from green (positive correlation) to dark orange (negative correlation) by increasing color density, significant correlation coefficients at p ≤ 0.05, ** p ≤ 0.01, and *** p ≤ 0.001.

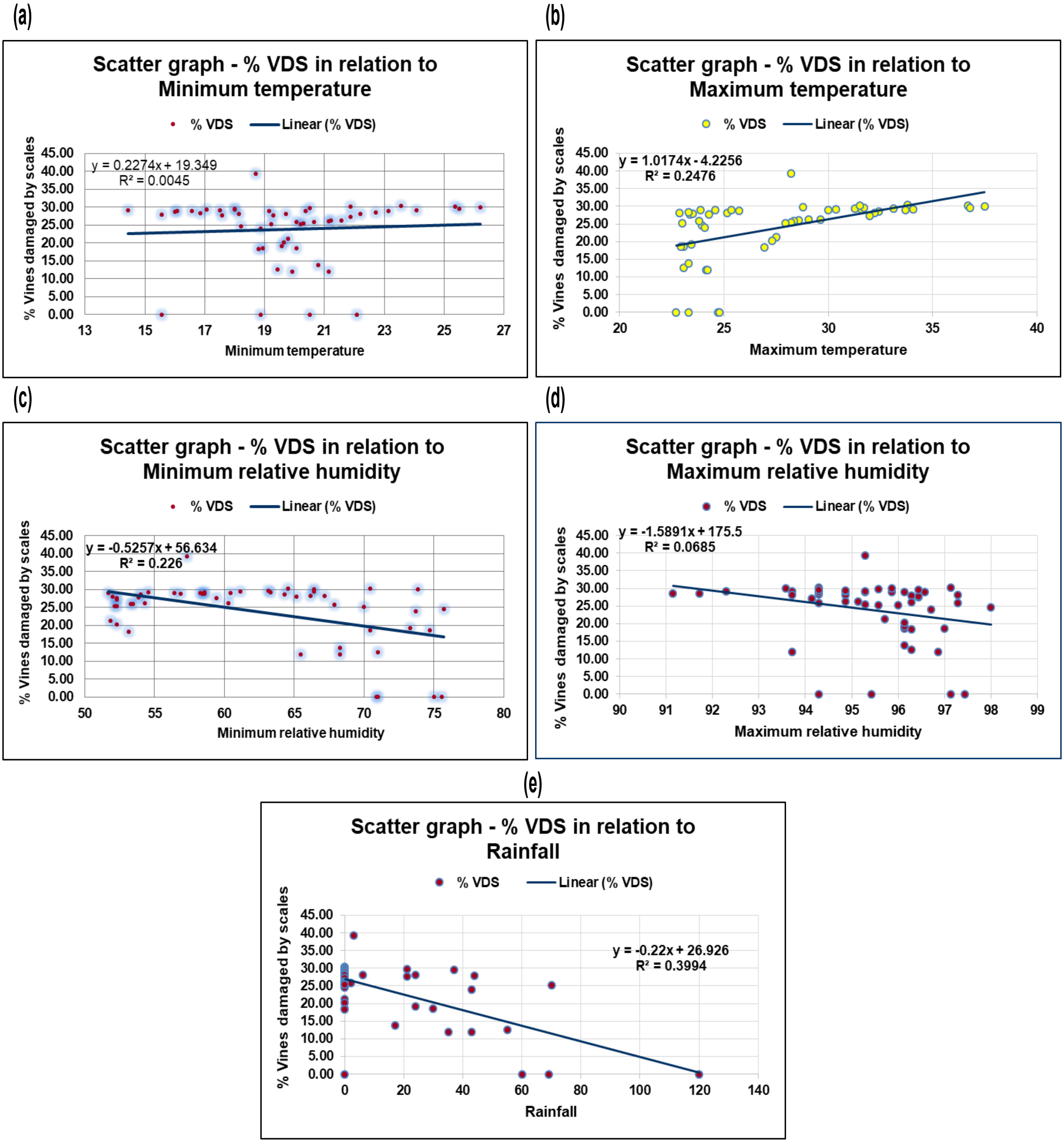

Fig. 9. Scatter graph of % vine damaged by scales (% VDS) in relation to weather factors (a) Minimum temperature (b) Maximum temperature (c) Minimum humidity (d) Maximum humidity (e) Rainfall.

Table 7. Multiple regression with % VDS and weather parameters

Weather parameters	Partial regression coefficients	Standard error	't' Value	R^2
Intercept	-10.088	70.232	-0.144	
X1 - Max. Temp (°c)	0.421	0.312	3.148	
X2 - Min. Temp (°c)	-0.326	0.480	-2.341	
X3 - Max. RH (%)	0.077	0.722	0.525	0.534
X4 - Min. RH (%)	-0.077	0.145	-0.526	
X5 - Rainfall (mm)	-0.476	0.045	-3.675	

N = 54, *Significant at p = 0.05 **Significant at p = 0.01, NS- Non Significant

Table 7a. Final run of linear regression model with the 3 most significant Independent variables

Variables	Coefficient	Standard Error	t-value	p-value	Rank of t-value
Rainfall	-0.220	0.038	-5.767	0.000	1
Max. Temp	0.525	0.245	2.138	0.038	2
Min. Temp	-1.211	0.428	-2.828	0.007	3

comprising solely these 3 variables significantly accounts for variations in % VDS. Analysis of the individual t-values indicates that rainfall is the most significant independent variable impacting %VDS, followed by maximum temperature and minimum temperature (Table 7a). Calculated MR coefficients for various weather-related variables (Table 7). The MR equation utilizing weather parameters for predicting % vine damage resulting from scales is as follows.

The coefficient of determination (R^2) was 53.4%, indicating the significance of these parameters in influencing the percentage of VDS in black pepper. This equation indicates that each unit increase in maximum temperature, maximum humidity results in increase of 0.421% and 0.077% in % VDS, correspondingly. Conversely, a 1-unit increase in minimum temperature, minimum humidity and rainfall will result in a decrease in % VDS by 0.326, 0.077 and 0.476, respectively. The results indicated that a linear regression analysis was conducted, utilizing multiple parameters that affect % VDS as the dependent variable, with weather conditions operating as the independent variable. The weather-based linear regression model could account for 53.4% of the variation in % VDS fluctuation along with variability.

Discussion

Seasonal incidence of leaf gall thrips in black pepper

The Shevroys hills of Tamil Nadu have been experiencing significant climate changes, particularly increased temperatures and reduced rainfall. Peak population of marginal gall thrips on black pepper was from January-February 2015 by (15). Infestation of leaf gall thrips on black pepper peaked during the monsoon season (June-September) (16). The occurrence of leaf gall thrips appeared from January to June, subsequently declining until November, with activity noted year-round; however, peak activity occurred from January - June 2015 (17).

Seasonal incidence of scales in black pepper

L. piperis population at Kalpetta occurred during summer months of February-May (14). Peak activity of the coffee scale, *Saissetia coffeae*, occurred from February-March, and that rainfall significantly reduced the prevalence of scale insects (18). Mussel scale on black pepper at Vellayani and they found highest population of mussel scale during second fortnight of April 2002 (19). A study recorded the seasonal population of *L. piperis* and *A. destructor,* and the population of *A. destructor* was low during April and steadily increased up to September (14). Population of *L. piperis* was low during July and August. From January onwards there was an increase in population. Mussel scale made its initial appearance (2.12 mussel scale/ leaf/vine) on black pepper crop in end weeks of November (48th SMW) at fruiting stage, that continued to build up with intermediately up and downs and reached its highest population (12.02 mussel scale/leaf/ vine) recorded during 1st week of February (6th SMW) in ripening stage (20). Thereafter, mussel scale continuously decreased its population with 6.03 mussel scale/leaf/vine during the last week of March (13th SMW). Presence of mussel scales was recorded from January - May 2013 (0.02 - 0.5 scales per 9 leaves), January - April 2014 (0.07-0.36 scales per 9 leaves) and January - March 2015 (0.02 - 0.7 scales per 9 leaves) (17).

Crest frequency reported 4 times (3rd, 9th, 13th and 21st standard weeks), 2 times (5th and 15th standard weeks) and 4 times (9th, 13th, 37th and 43rd standard weeks) during years 2013, 2014 and 2015 correspondingly. Mussel scale on black pepper at Vellayani and they found highest population of mussel scale during second fortnight of April 2002 (17). *L. piperis* population reported during summer months (January -May) (15). Association of weather factors temperature and RH with population dynamics of green bugs and mealy bugs in orange in Shevroy hills of Tamil Nadu during dry periods that had high population and damage. Current study indicates that rainfall had significant negative impact with on % spikes damaged by scales and % vines damaged by scales (21). Rainfall adversely affected *L. piperis* and *A. destructor* in black pepper (16). Ambient maximum temperature and minimum temperature as well as RH significantly influenced abundance of mealybugs in mango, accounting for 24.7% of the variance (22). This result closely aligns with current research. During present research population and damage caused by sucking pests of black pepper was assessed for a year from 2021 - 2022 in Horticultural Research Station, Yercaud.

% Leaf damaged by thrips in relation to weather factors

Damage of leaves by leaf gall thrips was maximum during 18th standard week 2021 *i.e.,* summer season. These are periods of low humidity and high temperature, that are congenial for buildup of pest population and subsequent damage. Minimum damage by leaf gall thrips was observed during 36th standard weeks. These observations corroborated with findings of (5, 15, 17). Thirty percent of vines under observation were infested by scale insects during 18th standard week 2021. However, only 12.00% infestation was recorded for 6 months. Intensity of scale insects was low during 40 - 46 standard weeks. There was an increase in percentage of vines damaged by scales from 47th standard weeks onwards. 14th standard weeks of 2021 when scale infestation was maximum were periods of high temperature that were congenial for multiplication of insect.

During summer season a maximum of 39.35% of vines were affected. Comparable findings were observed in another investigation, where leaves afflicted with leaf gall thrips substantially correlated with both maximum and minimum temperatures (14). Maximum relative, minimum RH and rainfall was significantly negatively correlated with leaf damage by leaf gall thrips. Temperature had been congenial for multiplication of gall thrips leaf damage. During rainy season, RH adversely affected different stages of pest development. Similar findings were already reported (5, 15).

% spikes damaged by scales in relation to weather factors

Percentage of spikes damaged by scales positively correlated to maximum temperature and negatively correlated to RH and rainfall. Temperature were congenial for multiplication of scales infestation on spikes. During rainy season and RH adversely affected different stages of pest. Similarly, Maximum temperature was found positively significant with % VDS, while minimum RH negatively significant with % VDS.

A statistically significant positive correlation with maximum temperature and remaining other factor displayed statistically significant negative correlation with maximum temperature, minimum temperature and average RH. This result closely aligns with current research (17). Similarly, it was reported that *Planococcus solenopsis* (Tinsley) infestation was higher in October on cotton and okra (23, 24). It was further mentioned that cassava root mealy bugs impact higher during dry season (25). A significant positive correlation amongst grape mealy bug populations with maximum temperature, as well as a negative correlation with RH. RH of 85% with a maximum temperature of 29 °C favored mealy bug population build-up in soil on roots of black pepper regression analysis had a 48% good fit with root mealybug population and weather parameters (26). Association of weather factors temperature and RH with population dynamics of green bugs and mealy bugs in orange in Shevroy hills of Tamil Nadu during dry periods that had high population and damage (21).

The current study indicates that rainfall had a significant negative impact with on percentage spikes damaged by scales and percentage vines damaged by scales. A study found that rainfall negatively impacted black pepper' *L. piperis* and *A. destructor* (16). About 24.7% ambient maximum temperature and minimum temperature and RH towards abundance of mealy bugs in mango (22). During the present study, rainfall influenced percantage leaf damage by leaf gall thrips by 36.5%. Current research is consistent with MR analysis, which demonstrated that rainfall affected the thrips population by 49% (R^2 = 0.4857), and a unit decrease in rainfall increased the thrips population by 0.01 in 2013 (17). The MR analysis displayed that maximum temperature and RH influenced the percent damage caused by scales by 40.6% and 36.4%. The present results thus align with the outcome of another investigation, where MR scrutiny exposed that morning RH influenced the population scale by by 51 % during 2015 (26).

The results underscore the need for targeted pest management interventions during peak periods, particularly for leaf gall thrips (*Liothrips karnyni*) and scale insects (*Aspidiotus destructor*). The cyclical nature of pest activity suggests that early detection and timely interventions are crucial for minimizing damage. Continuous monitoring and long-term strategies are necessary for managing sustained pest threats, especially given the consistent presence of scale insects and the gradual increase in damage. These findings support broader Integrated Pest Management (IPM) strategies, including population monitoring, predictive modeling, and adaptive interventions in response to climate change. Ecological niche models (ENMs) can predict shifts in pest distributions and identify suitable habitats under future climate scenarios (27). Crop rotation and diversification effectively reduce pest outbreaks and managing diseases exacerbated by climate change (28). Furthermore, the potential impact of temperature extremes on insect biology and biocontrol efficacy highlights the need for adaptive strategies, including understanding of tritrophic relationships (29, 30). Lastly, the enhancing thermal tolerance through Tsl gene mutations may improve the effectiveness of the sterile insect technique (SIT) in warmer climates (31). By integrating these strategies, agricultural systems can become more resilient to the challenges posed by climate variability.

Conclusion

In conclusion, this study highlights the significant influence of weather factors on the infestation dynamics of leaf gall thrips and scales in black pepper, emphasizing the complex interactions between climatic conditions and pest activity. The findings demonstrate that temperature and relative humidity are critical for managing leaf gall thrips, with peak infestations occurring during warmer, moderately humid periods. Conversely, scale insect populations are more prevalent during the monsoon, correlating with high rainfall and sustained humidity levels. These insights underline the importance of weather-responsive pest management strategies, recommending that pest control interventions be adjusted seasonally to align with anticipated weather patterns. Integrating climate data into pest management frameworks could help farmers and agricultural stakeholders make informed decisions, minimizing pest-related damage and maximizing yield. By adopting adaptive management practices, the black pepper industry can better mitigate the impact of climate variability on pest infestations, supporting sustainable pepper production in an era of changing environmental conditions.

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Authors' contributions

SKM carried out the experimental trials and wrote the manuscript. JPS was involved in writing the methodology. SKP was involved in the data analysis. DM was involved in the editing and corrections. AP was involved in data analysis. GK participated in the statistical analysis. SK participated in the graphical representation, and SB was involved in the overall corrections of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors' do not have any conflicts of interest to declare.

Ethical issues: None

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