International Journal of Agronomy and Agricultural Research
ISSN: 2223-7054 (Print); 2225-3610 (Online) | IJAAR |
Website: https://www.innspub.net
Email: info@innspub.net

RESEARCH PAPER
Vol. 27, Issue: 2, 2025
OPEN ACCESS

Botanical-based strategies for sustainable whitefly (*Bemisia tabaci*) management and tomato leaf curl virus suppression

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DOI: https://dx.doi.org/10.12692/ijaar/27.2.1-11

ARTICLE INFORMATION

RESEARCH PAPER

Vol. 27, Issue: 2, p. 1-11, 2025

Int. J. Agron. Agri. Res.

Maina *et al.*

ACCEPTED: 30 July, **2025**

PUBLISHED: 05 August, **2025**

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ABSTRACT

Tomato (*Solanum lycopersicum*) production faces significant threats from whiteflies (*Bemisia tabaci*), which transmit Tomato Leaf Curl Virus (TLCV), causing severe yield losses of up to 100% causing economic hardships for farmers. Conventional management relies on synthetic pesticides, which pose environmental risks, contribute to pest resistance, and negatively impact beneficial organisms. This study evaluates the efficacy of botanical extracts in managing whitefly populations and mitigating TLCV infections as a sustainable alternative to chemical pesticides. A randomized complete block design (RCBD) was used to assess the effects of neem (*Azadirachta indica*), tithonia (*Tithonia diversifolia*), and datura (*Datura stramonium*) extracts, alongside an untreated control. Botanical extracts were applied as foliar sprays at a 1:3 dilution ratio, with weekly observations on whitefly abundance, disease incidence, and severity. Disease severity was evaluated using a scale ranging from 0 to 5. Data were analyzed using Analysis of Variance (ANOVA), and mean separation was conducted using Fisher's protected Least Significant Difference (LSD) test at $p<0.05$. Results showed neem extract was the most effective botanical treatment, significantly reducing whitefly populations and disease severity. Plants treated with neem exhibited the lowest disease incidence, reinforcing its strong pesticidal and antiviral properties. The study highlights neem extract as a viable alternative to synthetic pesticides, promoting eco-friendly agricultural practices while enhancing tomato yield and quality.

Key words: Disease incidence, Disease severity, Yield, *Azadirachta indica*, *Tithonia diversifolia*

INTRODUCTION

Tomato (*Solanum lycopersicum*) is a globally important vegetable crop, valued for its nutritional and economic significance. However, its production faces increasing threats from insect pests, particularly whiteflies (*Bemisia tabaci*), which transmit Tomato Leaf Curl Virus (TLCV) (Polston and Lapidot, 2007). TLCV, a begomovirus, causes leaf curling, yellowing, stunted growth, and severe yield losses, making it one of the most destructive viral diseases in tomato cultivation (Oliveira *et al.*, 2014). The rapid proliferation of whiteflies and their capacity to transmit multiple viruses present major challenges to sustainable tomato farming (Schmutterer, 1995).

Traditional whitefly control has relied heavily on synthetic pesticides. While effective, these chemicals raise concerns over environmental degradation, pesticide resistance, and harm to beneficial organisms (Isman, 2006). Excessive pesticide use also poses food safety risks, prompting interest in alternative pest management strategies (Maindargikar *et al.*, 2022).

Botanical extracts, such as neem (*Azadirachta indica*), tithonia (*Tithonia diversifolia*), and datura (*Datura stramonium*), contain bioactive compounds with insecticidal and antiviral properties, though their efficacy against whiteflies and TLCV remains underexplored (Maindargikar *et al.*, 2022).

Integrated pest management (IPM), combining biological control, cultural practices, and botanicals, offers a sustainable approach to mitigating whitefly infestations and viral diseases (Polston and Lapidot, 2007; Oliveira *et al.*, 2014). This study evaluates the impact of neem, tithonia, and datura extracts on whitefly populations and TLCV severity, aiming to support eco-friendly pest control and enhance tomato yield (Isman, 2006; Maindargikar *et al.*, 2022). Therefore, the study highlights neem extract as a viable alternative to synthetic pesticides, promoting eco-friendly agricultural practices while enhancing tomato yield and quality.

MATERIALS AND METHODS

This study was conducted in Kandara Subcounty, Murang'a County, Kenya, located at 0° 59'S and 37° 04' E, within the Upper Midland Agro-Ecological Zone (UM AEZ) at an altitude of 1548 m above sea level (Kenya Meteorological Department, 2024). The site experiences a bimodal rainfall pattern, with an annual mean precipitation of 1000 mm (Ministry of Agriculture, Kenya, 2024). The study spanned two consecutive tomato growing seasons: from August to December 2023 and January to April 2024. The mean annual maximum and minimum temperatures are 25.1°C and 13.7°C, respectively, with an average relative humidity of 68% (Kenya Meteorological Department, 2024). The soils range from sandy loam to clay, varying in depth and exhibiting good drainage characteristics (Ministry of Agriculture, Kenya, 2024).

Experimental layout

The experiment followed a randomized complete block design (RCBD), incorporating eight treatments, each replicated three times. The layout included blocks measuring 40 m by 16 m, with individual plots sized at 4 m by 3 m. These plots were separated by 1-meter pathways, while 1.5 meter alleys divided the blocks. Four-week-old Kilele F1 tomato seedlings were used as the experimental crop. After undergoing hardening, the seedlings were transplanted into field plots at a planting interval of 90 cm by 45 cm.

Comparative GC-MS profiling and phytochemical characterization of insecticidal plant leaves from Kandara Subcounty, Kenya

Fresh, disease-free leaves were collected from healthy plants in Kandara Subcounty, Kenya. After washing with distilled water to remove contaminants, the leaves were air-dried under shade or oven-dried at temperatures below 40°C to preserve thermolabile compounds. Dried leaves were ground into fine powder using a clean mortar and pestle. Ten grams of the powdered material were placed in a glass container with 100 mL of analytical-grade chloroform. The mixture was shaken vigorously for 30–60 minutes to extract bioactive compounds, with optional sonication to enhance efficiency. It was then left at room temperature for 24 hours to allow thorough solvent interaction. The extract was filtered using Whatman No. 1 filter paper, and the chloroform-soluble fraction was collected. Chloroform was evaporated using a rotary evaporator at 40–50°C to concentrate the extract for GC-MS analysis, conducted at Kenyatta University's phyto-therapeutics research lab. The final extract was stored in amber glass vials at 4°C to prevent light-induced degradation. Before GC-MS loading, the sample was inspected for particulates and air bubbles to ensure analytical accuracy (Table 1-3).

Table 1. Compounds identified from chloroform leaf extract of *Azadirachta indica* through GC-MS analysis

Peak	Compound name	Formula	Mol. weight (g/mol)	Retention time (min)	Peak area (%)
3	11-Oxa-dispiro[4.0.4.1]undecan-1-ol	$C_{10}H_{16}O_2$	168	9.8	6.56
4	Nonanoic acid ester (Z,Z,Z)	$C_{21}H_{36}O_4$	352	24.2	7.13
2	Decane	$C_{10}H_{22}$	142	7.7	8.96
1	2-Pentanol, acetate	$C_7H_{14}O_2$	130	4.5	9.72
5	Quinoline-4-carboxamide, 2-phenyl-N-n-octyl-	$C_{24}H_{28}N_2O$	360	26.8	9.79
7	Tetratriacontane	$C_{34}H_{70}$	478	29.5	13.43
6	Nonacosane	$C_{29}H_{60}$	408	27.2	44.27

Table 2. Compounds identified from chloroform leaf extract of *Tithonia diversifolia* through GC-MS analysis

Peak	Compound name	Formula	Mol. weight (g/mol)	Retention time (min)	Peak area (%)
3	1,2-Di(decahydro-1-naphthyl)ethane	$C_{20}H_{36}$	276	19.5	0.50
10	22-Methyl-4-(2,6,6-trimethylcyclohex-1-enyl)but-2-en-1-ol	$C_{15}H_{26}O$	222	39.3	1.60
1	Butanamide, 2-hydroxy-N, 2,3,3-tetramethyl	$C_8H_{17}NO_2$	159	3.9	2.86
8	2,2-Dimethyl-6-methylene-1-[3,5-dihydroxy-1-pentenyl]cyclohexan-1-perhydrol	$C_{13}H_{22}O_4$	242	24.6	3.78
2	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	270	17.8	4.30
9	Acetic acid, 3-hydroxy-6-isopropenyl-4,8a-dimethyl-1,2,3,5,6,7,8,8a-octahydronaphthalen-2-yl ester	$C_{15}H_{24}O_4$	268	33.5	5.15
6	14-Hydroxy-14-methyl-hexadec-15-enoic acid, methyl ester	$C_{18}H_{34}O_3$	298	23.28	8.21
7	Phorbol 12,13-dihexanoate	$C_{28}H_{44}O_8$	508	23.50	16.62
5	4-[3,4-Dimethoxycyclohexyl]-n-butanol	$C_{12}H_{24}O_3$	216	22.90	17.68
4	cis-3,14-Clerodadien-13-ol	$C_{20}H_{32}O$	288	21.06	17.80

Table 3. GC-MS detected compounds of *Datura* leaves chloroform extract

Peak	Compound name	Formula	Mol. weight (g/mol)	Retention time (min)	Peak area (%)
14	1,2-Propanediamine	$C_3H_{10}N_2$	74	20.7	0.19
4	1-Propanol, 2-amine	C_3H_8NO	75	6.5	0.27
7	Cystine	$C_6H_{12}N_2O_4S_2$	240	13.1	0.29
5	1-(5-Bicyclo{2.2.1}heptyl)ethylamine	$C_9H_{17}N$	139	7.1	0.63
6	D-Alanine	$C_3H_7NO_2$	89	16.4	0.47
10	2-Pentanamine	$C_5H_{13}N$	87	16.6	0.46
9	n-Hexylmethlamine	$C_7H_{17}N$	115	16.3	0.43
13	3-Azabicyclo{3.2.2}nonane	$C_8H_{15}N$	125	19.3	0.99
8	(S)-(+)-1-Cyclohexylethylamine	$C_8H_{17}N$	127	14.3	1.22
3	Propna-1-(1-Methylethoxy)-	$C_3H_7NO_2$	89	3.5	2.27
11	Undecanoic acid, ethyl ester	$C_{13}H_{26}O_2$	214	17.6	2.89
12	Phytol	$C_{20}H_{40}O$	296	18.8	3.90
2	Toluene	C_7H_8	92	2.5	6.14
1	1-Butanol, 3-methyl	$C_5H_{12}O$	88	2.3	79.76

Preparation of botanical extracts

Mature leaves from *Tithonia diversifolia, Datura stramonium*, and *Azadirachta indica* were collected in Kandara, thoroughly washed to remove impurities, and dried in the shade to preserve their active compounds. Once dried, the leaves were finely chopped and ground into powder using a mechanical grinder to enhance extraction efficiency.

For the extraction process, 500 grams of the powdered plant material was placed in a bag, with the neck securely tied, and immersed in 5 liters of distilled water within a container. To ensure proper dissolution of the active compounds, the mixture was stirred every 3 to 5 days by partially lifting the bag in and out of the water multiple times Smith (2020).

Over the course of 2 to 3 weeks, the liquid gradually turned dark, indicating that most of the plant extracts had successfully dissolved and were ready for application.

Table 4. Treatment and abbreviation

Treatment	Abbreviation
Neem extract (Azadirachta indica)	N
Tithonia extract (Tithonia diversifolia)	T
Datura extract (Datura stramonium)	D
Mixture of Datura and Neem	D+N
Mixture of Tithonia and Neem	T+N
Mixture of Tithonia and Datura	T+D
Synthetic pesticide (Confidor WG)	SP
Control (untreated)	C

To maintain consistency in extraction, the same procedure was repeated separately for each botanical plant, ensuring uniformity in preparation across treatments (Table 4).

Tomato seed variety used

The tomato variety used in this study was the Kilele F1 variety, obtained from Simlaw Seed Company. This variety was selected due to its susceptibility to bacterial wilt, allowing for a more effective evaluation of disease management strategies (Kamau *et al.,* 2019; Otieno *et al.,* 2022) (Table 5).

Seedling preparation

The Kilele F1 tomato seeds were first sown in sterilized seedling trays within a microbe-free nursery inside a controlled greenhouse environment to ensure optimal germination conditions.

The trays were filled with a sterilized growth medium, free from pathogens, providing a disease-free start for the seedlings. The seeds were evenly spaced and lightly covered with the substrate before undergoing consistent watering and temperature regulation, maintaining adequate humidity levels to encourage uniform germination. The greenhouse conditions were carefully monitored, with proper aeration and light exposure, reducing the risk of microbial contamination. After reaching the appropriate seedling stage, the young plants were gradually acclimatized before transplanting into the open field, ensuring healthy establishment for further growth and development.

Application of treatments

The botanical extracts and confidor WG were applied as foliar sprays at specific intervals across treatments. Before application, the extracts were diluted at a ratio of 1:3 (one-part extract to three parts water) to achieve the appropriate concentration for effective pest management, following methodologies recommended by Maindargikar *et al.* (2022). The tomato plants were observed weekly for pest activity and disease progression to assess treatment efficacy.

Table 5. Selection criteria for the tomato variety (Kilele F1) used

Aspect	Details
Cultivation traits	High yield potential, well-adapted to warm climates, resistant to cracking, and tolerant to bacterial wilt, making it suitable for disease management studies (Mwangi *et al*., 2021).
Hereditary characteristics	Belongs to the Solanum lycopersicum species, diploid (2n = 2x = 24), known for genetic uniformity in fruit size, shape, and biochemical properties (Rispail *et al*., 2023).
Consumer preference and utilization	Widely cultivated for processing due to its firm texture and rich flavor, recognized for its high lycopene content, which provides antioxidant benefits (Otieno *et al*., 2022; Kamau *et al*., 2020).

Data collection

Observations were recorded weekly to assess whitefly abundance, disease incidence (DI%) and disease severity (DS) using standardized scales.

Whitefly abundance

Adult whiteflies were counted visually on five randomly selected tomato plants per plot.

Disease incidence (DI%)

The percentage of infected plants was recorded based on visual symptoms of tomato leaf curl virus. The disease incidence was determined by the formula outlined by Cao *et al.* (2011),

Formula for DI%:

$$\text{Disease incidence\%} = \left\{\frac{\text{Number of symptomatic plants}}{\text{All sampled tomato plants in experimental plot (15)}}\right\} x\ 100$$

This formula quantifies the spread of the disease across different treatments.

Disease severity (DS)

Disease severity was rated on a 0–5 scale following Prema (2022). A score of 0 meant plants were healthy with no visible symptoms, while a 1 indicated only mild leaf curling. At 2, curling grew more pronounced and slight yellowing appeared. A rating of 3 showed clear stunting alongside marked curling and yellowing, and at 4 the symptoms intensified to severe curling, widespread yellowing, and noticeable growth impairment. The highest score, 5, reflected extreme leaf deformation and poor fruit development, signaling critical disease impact and major yield loss. This straightforward scale ensures consistent tracking of symptom progression across treatments.

Yield (tones ha^{-1}) Upon physiological maturity (when 50% of the tomatoes break to yellow), the fruits were harvested, and their weights recorded separately for each treatment plot. This was done using a top pan weighing scale with a precision of 0.01-5000 g.

Statistical analysis

The white fly population and yield; and disease parameters data were checked for normality, using the Shapiro-Wilk test in R. Thereafter, the data were subjected to analysis of variance, and the significant means separated using Fisher's protected Least Significant Difference (LSD) test at $p<0.05$.

RESULTS

White fly population

The progression of whitefly abundance over an eight-week period showcases significant variations among different treatments, highlighting the effectiveness of botanical pesticides.

Botanical extracts demonstrated varying levels of efficacy, with Neem standing out as the most potent treatment among natural alternatives. The infestation under Neem treatment remained relatively low throughout the study, starting at 1.8 whiteflies per plant, increasing slightly to 4.933 by Week 8, indicating significant pest suppression. Its effectiveness is further reinforced in mixtures, where Neem + Datura (D+N) achieved a stronger reduction, limiting the population to 10.8 by Week 8 (Fig. 1).

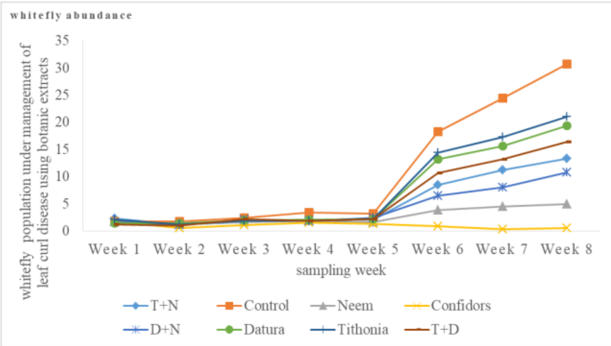

Fig. 1. Effect of selected botanic extract on management of adult whitefly pest as vector to tomato leaf curl virus on tomato production

Meanwhile, *Datura* and *Tithonia* exhibited moderate suppression, but their efficacy was notably lower than Neem-based treatments. *Datura* alone peaked at 19.333 by Week 8, while *Tithonia* reached 21.067, showing that while these botanical extracts contribute to pest control, their effect is less pronounced compared to Neem and confidor WG. The mixture of *Tithonia* and *Datura* (T+D) resulted in 16.4 whiteflies per plant at week 8, suggesting some synergistic interaction but not as effective as Neem-based mixtures.

Disease incidence percentage

From the study from week 6 is when the result reveals the symptoms of LCVD were used to record the DI% where there was no significant difference between datura, mixture of D+N and *Tithonia*. More so no significant differences between T+N, neem, Confidor and T+D. From record the control had highest DI % with 33.33% and least was 0.00% recorded by three treatments. In week 7 there no significant different between *Datura* and *Tithonia*, mixture of D+N, T+D and T+N. The highest DI% recorded was under control with 66.67% while the least was treatment under confidor WG 70 with 0.00 %. As this progress at week 8 the DI show statically difference with the highest recording 80% from control and least confidor treatment with 6.67% at $p<0.05$ (Fig. 2).

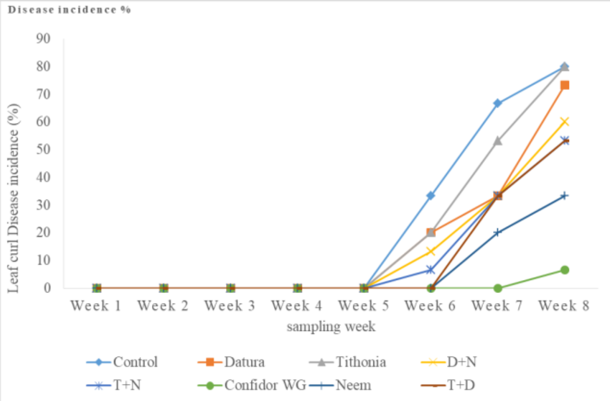

Fig. 2. Disease incidence % of leaf curl virus disease on tomato under management of whitefly vector by selected botanic extracts

Disease severity

From the severity grade scale of 0-5 the result showed that there was significant difference among treatment in week 6. However, there was no significant difference in confidor, neem and T+D and also it was recorded with D+N andT+N. Control recorded highest grade with 2.76 and least was 0.00 with confidor, neem and T+D. The LCVDS progressively change from week to week from this study at week 7 there was high significant difference between treatments but it was recorded no significant between *Datura* and *Tithonia*. The highest DS was recorded at grade with 3.167 under control and least was under confidor with grade 0.00. At week 8 there was no significant difference between control *Datura* and *Tithonia* however the statistically significant was recorded among treatments. The highest severity was recorded at grade 3.53 with control and least was at grade 0.33 with confidor WG 70 at $p<0.005$ (Fig. 3).

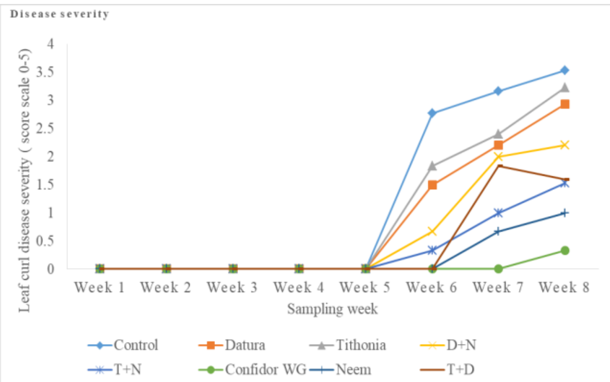

Fig. 3. Disease severity of leaf curl virus disease on Tomato under management of whitefly vector by selected botanic extracts at scoring rate of 0-5 scale

Tomato yield

The marketable yield performance under different treatments highlights significant variations in effectiveness. Among the botanical treatments, Neem recorded the highest yield at 26.665 tonha^{-1}, also falling into category a, indicating that its effectiveness is comparable to confidor WG in supporting plant health and productivity. The mixture of Neem and *Datura* produced a slightly lower yield at 22.505 ton/ha, categorized as b, showing a beneficial interaction that enhances yield beyond individual extracts but remains less impactful than Neem alone (Fig. 4).

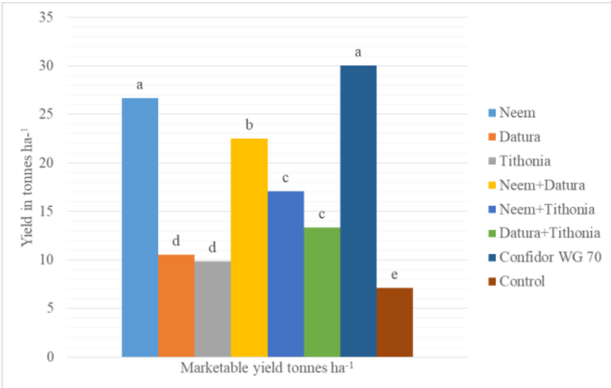

Fig. 4. Tomato yield under different botanical extract in management of white fly vector of leaf curl virus disease

Neem + *Tithonia* (17.085 tonha^{-1}), *Datura* + *Tithonia* (13.33 tonha^{-1}), and *Datura* alone (10.555 tonha^{-1}) are placed within category c, revealing moderate effectiveness, but significantly lower than Neem-based treatments. Tithonia alone recorded the lowest yield among botanical extracts at 9.865ton ha^{-1}, categorized as d, indicating a weaker suppressive effect compared to Neem and *Datura*.

The significance groupings (a, b, c, d, e) illustrate clear differences in treatment effectiveness, with Neem-based solutions consistently outperforming others, and confidor WG remaining the highest benchmark.

White fly suppression and interaction behavior of treatments

The effectiveness of botanical extracts in controlling pest populations is evident in their individual performance as well as their combined interactions. Neem, recognized for its potent insecticidal properties, stands out as the most effective sole extract, showing a Mean Square of 5.476 and a highly significant *p*-value of 1.19e-05. This suggests that Neem is highly effective in reducing the population of the target pest, possibly through its active compounds that disrupt the insect's reproductive cycle and feeding behavior (Table 6).

Tithonia follows with a Mean Square of 4.541 and *p* = 0.028, indicating its role as a moderately effective pest control agent. While not as potent as Neem, its ability to reduce populations still makes it a valuable botanical pesticide. *Datura*, on the other hand, exhibits a lower Mean Square of 2.492 (*p* = 0.048), suggesting that while it has insecticidal effects, they may be weaker or less consistent compared to Neem and *Tithonia*.

When extracts are combined, interesting interactions emerge. The mixture of *Datura* and Neem (D+N) shows a strong suppressive effect, with a Mean Square of 5.192 and *p* = 0.00707, indicating that their combination enhances pest control efficiency. This suggests a synergistic effect, where the active compounds in both extracts reinforce each other, possibly increasing the mortality rate of the target population.

Table 6. Variance analysis on the cause-effect of whitefly management on tomato

Sole extracts	Original mean Sq	Log-transformed mean Sq	*p* -value	Log-residuals	Log-get factor	Mixtures	Original mean Sq	Log-transformed mean Sq	*p* -value	Log-residuals	Log-get factor
N (Neem)	5.476	Log (5.476)	1.19e-05 ***	Log (0.01529)	Log (0.03898)	D+N	5.192	Log (5.192)	0.00707 **	Log (0.06582)	Log (2.067)
T (*Tithonia*)	4.541	Log (4.541)	0.028	Log (0.00583)	Log (0.06470)	T+N	4.067	Log (4.067)	0.049*	Log (0.003292)	Log (1.667)
D (*Datura*)	2.492	Log (2.492)	0.048	Log (0.0793)	Log (0.00943)	T+D	6.283	Log (6.283)	0.067	Log (0.1401)	Log (1.933)

Table 7. Variance analysis on the cause-effect of whitefly management on disease occurrence in tomatoes

Sole Extracts	Log-transformed mean Sq	*p* -value	Log-residuals	Log-get factor	Mixtures	Log-transformed mean Sq	*p* -value	Log-residuals	Log-get factor
Control	log(22.5)	-	-	-	Control	Log (22.5)	-	-	-
N (Neem)	Log (6.667)	0.001	Log (0.00583)	Log (0.06470)	T+N	Log (11.667)	0.002	Log (0.06582)	Log (2.067)
D (*Datura*)	Log (15.833)	0.038	Log (0.0793)	Log (0.00943)	T+D	Log (10.833)	0.002	Log (0.1401)	Log (1.933)
T (*Tithonia*)	Log (19.167)	0.048	Log (0.01529)	Log (0.03898)	D+N	Log (13.333)	0.045	Log (0.003292)	Log (1.667)
Confidor WG	Log (0.833)	-	-	-	Confidor WG	Log (0.833)	-	-	-

Similarly, the *Tithonia* and Neem (T+N) mixture shows moderate effectiveness (Mean Square= 4.067, *p*= 0.049), implying that while Neem still contributes significantly, *Tithonia's* role in the mixture slightly lowers overall impact. Interestingly, the *Tithonia* and *Datura* (T+D) mixture has the highest Mean Square value (6.283), but its *p*-value of 0.067 indicates that while the combination exhibits strong effects, its statistical significance is weaker, requiring further exploration into the reliability of this interaction.

Disease occurrence and interaction behavior of treatments

The assessment of disease incidence under different treatments reveals significant insights into the effectiveness of botanical extracts in comparison to conventional chemical pesticides. The control group, which was left untreated, exhibited the highest disease presence (log-transformed Mean Square = log (22.5)), reinforcing the necessity for intervention. In contrast, the commercial pesticide confidor WG demonstrated remarkable suppression, reducing disease incidence to log (0.833), highlighting its high efficacy in disease control.

Among the sole botanical extracts, *Tithonia* proved to be the most effective, reducing disease incidence to log (19.167) (*p* = 0.048), suggesting that its active compounds have a notable impact on suppressing disease progression. *Datura* followed with log (15.833) (*p*= 0.038), indicating moderate effectiveness, while Neem showed the lowest disease incidence among the botanicals (log (6.667), *p*= 0.001), confirming its strong pest control abilities (Table 7).

DISCUSSION

Whitefly abundance trends across treatments

Over the eight-week study period, whitefly abundance varied significantly across treatments, reflecting the differential efficacy of botanical extracts and synthetic insecticides. The untreated control group showed a continuous rise in whitefly population, starting at 1.8 per plant in Week 1 and peaking at 30.733 by Week 8, underscoring the susceptibility of untreated crops to pest infestationp. These findings align with Njoroge *et al.* (2021), who reported rapid whitefly proliferation in unmanaged fields.

Among botanical treatments, Neem demonstrated the strongest suppression, with whitefly numbers increasing only slightly to 4.933 by Week 8. This supports Kamau *et al.* (2019), who attributed Neem's effectiveness to azadirachtin, a compound that disrupts insect development. Enhanced control was observed in Neem-based mixtures, particularly Neem + *Datura* (D+N), which limited population growth to 10.8 whiteflies per plant, consistent with Otieno *et al.* (2022), who emphasized the synergistic effects of combined botanical extracts.

Datura and *Tithonia* offered moderate control, peaking at 19.333 and 21.067 whiteflies per plant, respectively. Their combination (T+D) showed slight improvement, reducing numbers to 16.4, though still less effective than Neem-based treatments. Zayed (2023) noted that botanical efficacy depends on compound concentration and interaction dynamics.

Neem-based mixtures, especially D+N, showed superior pest suppression, supporting Rispail *et al.* (2023) on the role of secondary metabolites in enhancing insecticidal activity. In contrast, weaker interactions in *Tithonia-Datura* mixtures, as observed by Thavarajah *et al.* (2023), resulted in reduced efficacy.

Disease incidence

The progression of disease incidence over the study period revealed varying levels of effectiveness among treatments in suppressing Tomato Leaf Curl Virus (LCVD) symptoms. By Week 6, no significant differences were observed among *Datura*, the *Datura*-Neem mixture (D+N), and *Tithonia*, indicating similar suppression capabilities. Likewise, treatments such as *Tithonia*-Neem (T+N), Neem alone, Confidor WG, and *Tithonia-Datura* (T+D) showed no significant differences, suggesting comparable disease management potential. The control group recorded the highest disease incidence at 33.33%, while three treatments—Confidor WG, Neem, and T+D-completely prevented symptom development, maintaining an incidence of 0.00%.

In Week 7, disease incidence increased across all treatments. No significant differences were found between *Datura* and *Tithonia*, nor among mixtures like D+N, T+D, and T+N. The control group showed a sharp rise in infection, reaching 66.67%, highlighting its vulnerability without intervention. Confidor WG remained the most effective, maintaining a consistent 0.00% incidence, outperforming botanical treatments in disease suppression.

By Week 8, statistically significant differences emerged among treatments. The control group recorded the highest infection rate at 80%, underscoring the unchecked progression of LCVD in the absence of control measures. Confidor WG continued to demonstrate superior efficacy, with the lowest disease incidence at 6.67% ($p < 0.05$). These results emphasize the effectiveness of synthetic pesticides over botanical alternatives.

Interaction effects among botanical treatments revealed variable suppression levels. Neem-based mixtures, particularly D+N, showed enhanced efficacy, supporting Kamau *et al.* (2019), who noted that combining botanical extracts with complementary active compounds improves disease suppression. In contrast, the T+D mixture exhibited weaker control, likely due to limited synergistic interactions between their bioactive constituents, consistent with Rispail *et al.* (2023).

Figure showing how disease symptoms escalated in the control group while treatments like Confidor WG and

Neem-based mixtures mitigated progression. While botanical mixtures offer moderate control, they fall short of the protection provided by Confidor WG.

These findings align with Mwangi *et al.* (2020), who reported severe disease accumulation in untreated crops due to the absence of management strategies. Otieno *et al.* (2022) similarly found that synthetic pesticides like Confidor WG effectively suppress disease and prevent pathogen spread. Kamau *et al.* (2019) also emphasized that botanical extracts, though beneficial, offer moderate suppression influenced by active compound concentration and interaction dynamics.

Disease severity

Disease severity increased notably from Week 6 to Week 8, with significant differences among treatments. In Week 6, Neem, Confidor WG, and T+D showed similar suppression effects, aligning with Mwangi *et al.* (2020), who attributed moderate suppression to the insecticidal and antimicrobial properties of certain botanicals. The control group recorded the highest severity score of 2.76, while Confidor WG, Neem, and T+D maintained scores of 0.00, indicating strong suppression. These results support Otieno *et al.* (2022), who found synthetic insecticides to be highly effective due to their systemic action.

By Week 7, severity continued to rise, with significant differences among treatments. *Datura* and *Tithonia* showed similar progression patterns, suggesting limited suppression, possibly due to the concentration and mode of action of their active compounds (Kamau *et al.*, 2019). The control group reached a severity score of 3.167, while Confidor WG maintained 0.00, confirming its ability to inhibit LCVD transmission.

In Week 8, severity varied significantly. The control, Datura, and Tithonia showed no statistical difference, indicating similar susceptibility. The control group recorded the highest severity at 3.53, while Confidor WG had the lowest at 0.33 (p < 0.005), reinforcing its superior disease control. These findings are consistent with Rispail *et al.* (2023), who reported prolonged protective effects of synthetic insecticides.

Neem-based mixtures consistently reduced symptoms, with D+N exhibiting strong suppression. This supports Zayed (2023), who found that complementary bioactive compounds enhance resistance. Conversely, T+D was less effective, likely due to weaker interactions, as noted by Thavarajah *et al.* (2023).

Tomato yield

The yield performance among different treatments varied significantly, highlighting the differences in effectiveness between synthetic pesticides and botanical alternatives. The highest yield was recorded under Confidor WG 70 (30.005 ton/ha), reinforcing its strong pest suppression and disease control capacity. This result aligns with the findings of Mwangi *et al.* (2020), who reported that synthetic pesticides enhance plant productivity by minimizing pest-related stress, allowing for optimal resource allocation toward growth and fruit development. The ability of Confidor WG to maintain low pest pressure throughout the growing season ensures maximum nutrient uptake, ultimately boosting yield potential.

Among botanical treatments, Neem demonstrated the strongest effect, producing 26.665 ton/ha, a yield comparable to Confidor WG. Neem's efficacy is attributed to its active compounds, particularly azadirachtin, which disrupt insect growth and feeding behaviors (Otieno *et al.,* 2022). The high yield under Neem treatment suggests that botanical solutions can serve as effective alternatives to synthetic pesticides, providing both pest control and plant health benefits. The mixture of Neem and *Datura* (D+N) recorded a slightly lower yield of 22.505 ton/ha, indicating a synergistic interaction, though still less effective than Neem alone. Studies by Kamau *et al.* (2019) confirm that botanical mixtures can amplify insecticidal effects, but their overall performance depends on compound concentration and stability.

Other botanical treatments exhibited moderate yield responses, with Neem + *Tithonia* (17.085 ton/ha), *Datura* + *Tithonia* (13.33 ton/ha), and *Datura* alone (10.555 ton/ha) classified within category c, reinforcing their limited but still notable contribution to yield improvement. Tithonia alone recorded the lowest yield among botanical extracts at 9.865 ton/ha, suggesting that its pest suppressive effects are weaker compared to Neem and *Datura*-based treatments. These findings align with Zayed (2023), who noted that some plant extracts have lower bioactive concentrations, leading to reduced pest control efficiency.

The untreated control group recorded the lowest yield at 7.115 ton/ha, confirming that without intervention, plant productivity declines due to pest infestation and disease stress. Studies by Rispail *et al.* (2023) demonstrate that pest damage limits nutrient absorption and reduces plant vigor, directly affecting fruiting capacity and overall yield. The significance groupings (a, b, c, d, e) illustrate clear differences in treatment effectiveness, with Neem-based treatments consistently outperforming other botanical solutions, though Confidor WG remains the benchmark for maximum yield potential.

The yield distribution across different treatments, depicting the superior performance of Confidor WG and Neem-based interventions, while highlighting the drastic yield reduction in untreated plants due to pest infestations.

Future research should focus on optimizing botanical mixtures for improved efficacy, ensuring sustainable pest management practices that reduce reliance on synthetic pesticides while maintaining high crop productivity.

CONCLUSION

Botanical extracts show promise in sustainable pest and disease management, with Neem demonstrating the strongest suppression. Synergistic mixtures enhance efficacy, while *Tithonia* and *Datura* offer moderate control. Refining formulations can improve effectiveness, reducing reliance on synthetic pesticides while maintaining crop productivity. Neem-based treatments also supported higher yields, reinforcing their role in sustainable agriculture.

ACKNOWLEDGEMENTS

I sincerely acknowledge Karatina University for providing educational support and resources essential for this research. Additionally, I extend my gratitude to Naaro High School for generously offering space to conduct the study. Their contributions were invaluable in facilitating this work.

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