**RESEARCH ARTICLE**

**Evaluation of Fungicides, Botanicals, and Smoke Water Against Wilt Complex Pathogens of** **Hot Pepper (*Capsicum annuum* L.) in Toke Kutaye District, West Shewa, Ethiopia**

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**Abstract**

Hot pepper stands as a crucial vegetable, spice, and condiment crop in Ethiopia, valued for its versatility as fresh produce, dried spices, and processed products, with both significant domestic and export demand. However, the productivity of hot pepper is hampered by hot pepper wilt disease, caused by various soil-borne pathogens, posing a major challenge to production. In response, this study aimed to enhance hot pepper production and productivity by developing effective wilt management strategies utilizing fungicides, botanicals, and smoke water solutions. The field experiment assessed the efficacy of different treatments in reducing disease incidence and severity compared to untreated plots. Results demonstrated significant differences (p < 0.05) among all treatments compared to the control. For Ralstonia solanacearum, the lowest mean disease incidence and severity were observed in plots treated with the commercial fungicide Definoconazole 25% EC (14.75% and 22.22%, respectively), correlating with a significant increase in pod yield (23.77 t/ha). Additionally, Rucinus leaf extract and Olea Europaea bark smoke water showed promising results in disease reduction and yield improvement, following closely behind the commercial fungicide. In the case of Fusarium oxysporum, the lowest mean disease incidence and severity were recorded in plots treated with Definoconazole 25% EC (36.89% and 27.41%, respectively), with Rucinus leaf extract and Olea Europaea bark smoke water demonstrating notable efficacy as well. Similarly, for Rhizoctonia root rot, the lowest mean disease incidence and severity were observed in plots treated with Definoconazole 25% EC (32.61% and 22.22%, respectively), with Ocimum lamiifolium leaf smoke water also exhibiting promising results. Economic analysis revealed Definoconazole 25% EC to be the most cost-effective option, with a significant net benefit and marginal rate of return. In conclusion, the evaluated fungicides proved effective and are readily applicable for farmers to manage wilt complex disease in their fields. Furthermore, Rucinus leaf extract, Olea Europaea bark smoke water, and Ocimum lamiifolium leaf smoke water emerged as highly effective and environmentally sustainable methods for controlling hot pepper wilt disease.

**Key words:** Botanicals, fungicide, Hot pepper, smoke water, wilt disease

**Introduction**

Hot pepper (*Capsicum annum* L.) holds significant importance as a spice and vegetable crop in tropical regions across the globe. Belonging to the Solanaceae family and the genus Capsicum, it stands as the second most important vegetable crop after tomato worldwide (Berhanu *et al*. 2011). Originating in Central and South America, its cultivation has spread widely, particularly propelled by Spanish and Portuguese influence, reaching tropical and sub-tropical regions globally (Grubben and Denton, 2004). Hot pepper serves both nutritional and economic roles, with its fruits utilized fresh, dried, or processed as spice and condiment products. It holds high domestic and export value, contributing significantly to the agricultural economy (Anonymous 2003). In Ethiopia, hot pepper bears substantial nutritional, medicinal, and economic significance. Rich in essential vitamins and minerals, it plays a vital role in providing dietary nutrition, particularly as a source of vitamins A, E, and C (Shumeta 2012; Zeleke and Derso 2015). The average daily consumption of hot pepper among Ethiopian adults is notably high, underscoring its dietary importance (MARC 2004). Despite its economic and nutritional value, hot pepper faces various challenges that impede its production and productivity. Among these challenges, the presence of bacterial and fungal pathogens poses significant threats across pepper-growing regions in Ethiopia (BARC 1999). Fusarium spp., Phytophthora spp., Rhizoctonia solani, and Cercospora capsica are common fungal pathogens, while Ralstonia solanacearum causes bacterial wilt, collectively contributing to the wilt complex affecting hot pepper (Shiferaw and Alemayehu 2014; Kassahun *et al*. 2016). This study aims to address the challenges posed by wilt complex pathogens in hot pepper cultivation by evaluating effective management strategies. Focusing on fungicides, botanicals, and smoke water solutions, the study seeks to identify optimal tactics for managing hot pepper wilt disease. Through field experiments shown the efficacy of various treatments was assessed, with disease reduction and yield improvement serving as key metrics for treatment effectiveness. The aim of this study is to enhance the production and productivity of hot pepper by developing effective wilt management strategies by evaluating the efficacy of selected fungicides, botanicals, and smoke water against wilt complex pathogens affecting hot pepper and this study also aims to provide valuable insights into the management of hot pepper wilt disease, offering practical solutions for farmers to enhance crop yield and mitigate disease risks in hot pepper cultivation.

**Materials and Methods**

The field experimental study was conducted at the Ambo University Research Farm, Guder Mamo Mezemir Campus Situated in the West Shewa Zone of the Oromia region, during the 2021 main cropping season, under natural rainfall conditions. The coordinates of the study area lie between 8° 59’ 00’’N latitude and 37°46’0’’E longitude, with an average elevation ranging from 1580.3 to 1900 m above sea level. The agro-ecology of the district encompasses diverse terrains, including 23% highland, 60% mid-altitude, and 17% lowland areas, typical of the sub-tropical zone. The district experiences a bi-modal rainfall pattern, with the main rainy season occurring from June to August and a shorter rainy season from April to May. The predominant soil type in the district is clay, with a slightly acidic pH ranging from 5.5 to 6.0. The average annual rainfall in the district ranges from 800 to 1100 mm (TKDANO 2020).

**2.1 Experimental Materials**

For the field experimental study evaluating fungicides, plant extracts, and smoke water solutions against hot pepper wilt complex pathogens, seeds of the Hot Pepper Oda Haro variety (susceptible variety) were sourced from the Bako Agricultural Research Center. The fungicides for testing were procured from pesticide shops in Addis Ababa, while the botanicals and smoke water solutions were prepared in the laboratory of the Department.

**2.2 Preparation of Plant Extracts**

Plant tissue samples were carefully washed with running tap water to remove debris, dried under shade, and subjected to forced circulation of heated air at 40°C in the laboratory to prevent deterioration. Subsequently, the dried samples were ground into a powder using an electrical grinder and stored at 4°C. Plant powders were then extracted with distilled water at a ratio of 1:10 (weight by volume) under stirring conditions at room temperature for 1 hour. After settling overnight, the homogenate was filtered through double-layered muslin cloth and clarified by centrifugation at 7000 x g for 30 minutes at 4°C. The resulting supernatant was sterilized by filtration through 0.22 µm sterile filters and stored at 4°C for further use in microbial growth inhibition assays.

**2.3 Preparation of Smoke Water Solution**

Smoke water solutions were prepared following the method described by Boucher and Meets (2004) with slight modifications. Dry materials of Olea Europaea bark, Olea Europaea leaf, leaf of Ocimum lamiifolium, and Rhizome of Echinops kebericho were burned in a stainless-steel barrel smoker using compressed air. The resulting smoke was bubbled through distilled water in a 500-mL graduated cylinder for 45 minutes. After the smoke had dissolved the water-soluble compounds, the solution was filtered through Whatman No.1 filter paper to remove particulate matter and stored for further use as the stock solution.

**2.4 Field Experimental Study**

**2.4.1 Crop Establishment**

Seeds of hot pepper were sown on beds and mulched until 50% of seedlings emerged to control weed germination. Management practices were applied until the seedlings were ready for transplanting, which occurred after 45 days after sowing. Transplants were planted with a spacing of 1m between blocks, 0.5m between plots, 0.5m between rows, and 0.4m between plants within rows. Each plot covered an area of 5m2, with a total experimental area of 365.4m2. Recommended fertilizers, including NPS and urea, were applied during transplanting and in split applications thereafter. Other agronomic practices were carried out as needed.

**2.4.2 Experimental Design and Treatments**

The field experiment was arranged in a Randomized Complete Block Design (RCBD) with three replications. Treatments included three fungicides (Difenoconazole 25% EC, Propiconazole 25% EC, and Funguran OH 50% WP), four botanical extracts (Eucalyptus citriodora, Justicia schimperiana, Datura stramonium, and Rucinus communis), four smoke water solutions (Olea Europaea bark, Olea Europaea leaf, leaf of Ocimum lamiifolium, and Rhizome of Echinops kebericho), and an unsprayed control. The plants were sprayed with the respective treatments at five intervals of 15 days, starting 55 days after transplanting when the first symptoms of disease appeared. Observations on disease incidence and severity were recorded before each spray treatment and 15 days after the last spraying. Recommended application rates per hectare were followed for fungicides, while botanical application rates were based on previous research findings.

**2.5 Data Collection**

**2.5.1. Disease Incidence**

Disease incidence was assessed by counting the number of plants showing symptoms of wilt complex disease in each treatment plot. The percentage disease incidence was calculated using the formula:

**2.5.2 Disease Severity**

Disease severity was visually estimated by assessing the percentage of leaf area affected by disease on nine randomly selected and pre-tagged plants within the three middle rows of each plot. Severity assessments were conducted at fifteen-day intervals, starting from the beginning of disease symptoms until 15 days after the final spray application. Disease severity in the untreated control plots reached a plateau and did not increase further. Disease severity ratings were recorded using a scale of 0 to 4 for Ralstonia solanacearum (Hashen Du *et al*. 2016: Table.1), a scale of 0 to 5 for Fusarium oxysporum (Ismail 2015: Table. 2), and a scale of 0 to 5 for Rhizoctonia solani (Mannai *et al*. 2018: Table.3). The severity ratings were then converted into Percentage Severity Index (PSI) for analysis using the formula:

**Table 1.** Scoring scale of Ralstonia solanacearum (Source: Hashen Du *et al.*(2016)

|  |  |  |
| --- | --- | --- |
| S. No | Rating Scale | Description |
| 1 | 0 | Asymptomatic |
| 2 | 1 | Miner symptoms with less than 20% wilted leaves |
| 3 | 2 | Moderate symptoms with 20-50% wilted leaves |
| 4 | 3 | Severe symptoms with 50-80% wilted leaves |
| 5 | 4 | dead plants |

**Table 2.** Scoring scale of Fusarium oxysporum (Source: Ismail 2015)

|  |  |  |
| --- | --- | --- |
| S. N | Rating Scale | Description |
| 1 | 0 | Healthy |
| 2 | 1 | One leaf yellowing |
| 3 | 2 | More than One leaf yellowing |
| 4 | 3 | One wilted leaf |
| 5 | 4 | More than one leaf wilted |
| 6 | 5 | Completely dead/wilted plants |

**Table 3.** Scoring scale of Rhizoctonia solani (Source: Mannai *et al.*2018)

|  |  |  |
| --- | --- | --- |
| S. N | Rating Scale | Description |
| 1 | 0 | Absence of visible lesions in the collar. |
| 2 | 1 | 1 to 25% of the collar covered with lesions |
| 3 | 2 | 26 to 50% of the collar covered with lesions |
| 4 | 3 | 50 to 75% of the collar covered with Lesions |
| 5 | 4 | Large lesions (> 75%) |
| 6 | 5 | Dead plant. |

**2.6. Area under Disease Progress Curve (AUDPC).**

AUDPC was computed from the PSI data recorded at each date of assessment as described by Campbell and Madden (1990).



Where, Yi= disease severity on the ith date, Y (i+1) = disease severity on the i+1th date, n = number of dates.

**2.7 Growth, Yield, and Yield Component Parameters**

Data on various growth parameters and yield components were collected to assess the impact of treatments on plant development and productivity.

* **Plant Height (cm):** Measured from ground level to the tip of terminal leaves at maturity using a ruler.
* **Number of Leaves per Plant:** Total number of leaves per plant counted at maturity from nine randomly selected plants, with the average used for analysis.
* **Leaf Length (cm):** Measured from base to tip of the leaf at physiological maturity using a ruler.
* **Leaf Diameter (cm):** Diameter of the leaf at maturity measured using digital callipers and expressed in centimetres.
* **Leaf Area (cm²):** Calculated by multiplying length and width (diameter) of each leaf.
* **Number of Primary Branches:** Total count of primary branches per plant at maturity from nine randomly selected plants.
* **Number of Secondary Branches:** Total count of secondary branches per plant at maturity from nine randomly selected plants.
* **Number of Nodes per Plant:** Average count of total nodes per plant at maturity from nine randomly selected plants.
* **Number of Pods per Plant:** Average count of total pods per plant at maturity from nine randomly selected plants.
* **Pod Length (cm):** Measured from base to tip of the pod at physiological maturity using a ruler, with the average of nine plants used for analysis.
* **Pod Diameter (cm):** Average pod diameter measured using digital callipers from nine randomly selected plants at maturity.
* **Marketable Pod Yield (t/ha):** Weight of healthy pods harvested from the net plot area of each treatment at harvest time, expressed in tons per hectare.
* **Unmarketable Pod Yield (t/ha):** Total weight of unmarketable pods, characterized by whitish colour, small size, and physical damage, measured from the net plot of each treatment at final harvest and expressed in tons per hectare.
* **Total Pod Yield (t/ha):** Sum of marketable and unmarketable pod yields measured in kilograms per plot and converted to tons per hectare.
* **Relative Yield Loss (RYL):** Percentage yield reduction due to wilt complex disease compared with the most protected plot, calculated using the formula:



Where, RYL = relative yield loss in Percent, Yp = yield from the maximum protected plots and YT = yield from other plots

**2.8 Statistical Analysis**

The data from field experimental studies were subjected to Analysis of Variance (ANOVA) using SAS (Statistical Analysis System) version 9.4, following a Randomized Complete Block Design (RCBD). Mean separation was performed using Least Significant Difference (LSD) at a 5% probability level. Additionally, correlations among disease parameters and all yield and yield components were computed at a 5% probability level to assess relationships between variables.

**3. Results and Discussion**

**3.1 Wilt Complex Diseases Associated with Hot Pepper Under Experimental Field**

Symptom logical characterization, aided by the pepper wilt pathogens field identification guide, facilitated the determination of the pathogens and assessment of disease data. Complex wilting symptoms were observed during the assessment period.

The initial symptoms of Bacterial wilt were evident at 55 days after transplanting, characterized by sudden wilting and yellowing of leaves, followed by stunted growth, discoloration, and eventual plant death. Especially, the wilted leaves retained their green colour and remained attached to the plant, even as the disease progressed, ultimately leading to complete wilting and plant death. These findings align with previous reports by Mihovilovich *et al*. (2017) and Monther and Kamaruzaman (2010), highlighting the variability in symptom expression under different environmental conditions. Further symptoms of bacterial wilt, such as vascular discoloration from light yellow to dark brown, were also observed, corroborating previous findings by Harveson *et al*. (2015).

Similarly, initial symptoms of Fusarium wilt included leaf chlorosis, upward and inward rolling of upper leaves, stunting, wilting, and eventual plant death. These observations are consistent with reports by MacHardy and Beckman (1981), emphasizing the characteristic brown vascular discoloration and leaf symptoms associated with Fusarium wilt. In addition to the above, post-emergence damping-off, wire stem, root rot, and necrotic spots on tap roots were observed in the plots, indicative of Rhizoctonia root rot. These manifestations are in line with previous reports by Lopez *et al*. (2009), underscoring the multifaceted damage caused by Rhizoctonia solani at various growth stages.

**3.2 Disease Incidence (%)**

Mean wilt complex disease incidence was meticulously recorded five times, with all treatments significantly influencing the incidence of all three pathogens compared to untreated controls. The highest disease incidence was observed in untreated plots, while plots treated with Difenoconazole 25% EC exhibited the least disease incidence for all three pathogens. Particularly, Rucinus communis leaf extract showed significant disease incidence reduction for both Ralstonia and Fusarium wilt, indicating its effectiveness comparable to commercial fungicides.

**3.3 Disease Severity Index (PSI)**

Disease severity was meticulously recorded at five intervals, demonstrating a significant reduction in severity across all treatments compared to untreated controls (Table. 4). The highest disease severity reductions for all three pathogens were achieved in plots treated with Difenoconazole 25% EC. Among plant extracts, Eucalyptus leaf extract and Rucinus communis leaf extract exhibited the lowest bacterial disease severity, while Eucalyptus leaf extract and Justicia schimperiana leaf extract showed lower Fusarium wilt severity compared to commercial fungicides (Fig. 1, 2 and 3) Additionally, smoke water solutions of Olea Europaea bark and Echinops kebericho Rhizome significantly reduced wilt severity compared to control plots (Table.5)

Overall, the findings suggest that foliar and root zone application of fungicides, botanicals, and smoke water could effectively mitigate disease spread and severity in hot pepper, highlighting their potential for integrated disease management strategies. These results are consistent with previous studies that demonstrated the efficacy of plant extracts in reducing disease incidence and severity, suggesting their role in inducing systemic resistance or directly inhibiting pathogen growth (Table. 4). The current study underscores the importance of exploring eco-friendly alternatives to synthetic pesticides for sustainable disease management in agricultural systems, aligning with global efforts towards environmentally responsible farming practices.

**Table 4.** Efficacy of fungicides, botanicals and smoke-water on wilt complex disease Incidence of Hot pepper

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | **Wilt complex pathogens** | | | | | |
| **Ralstonia** | | **Fusarium** | | **Rhizoctonia** | |
| Mean DI (%) | MeanDI reduction (%) | MeanDI (%) | MeanDI reduction (%) | Mean DI (%) | MeanDI reduction (%) |
| T1 (DSLE) | 26.17def | 40.12e | 54.11bc | 37.63cd | 41.99bcd | 49.80c |
| T2 (ECLE) | 25.94def | 40.66d | 47.52cd | 45.23bc | 50.47bc | 39.65ef |
| T3 (JSLE) | 35.70abc | 18.31efg | 49.33bcd | 43.15bc | 55.98b | 33.07f |
| T4 (RCLE) | 24.79ef | 43.27d | 45.27cd | 47.83b | 49.04bcd | 41.36e |
| T5 (EKRS) | 37.65ab | 13.87h | 62.62b | 27.82f | 48.85bcd | 41.60e |
| T6 (OEBS) | 24.04ef | 45.00d | 50.42bcd | 41.88cd | 45.56bcd | 45.53d |
| T7 (OELS) | 33.75bcd | 22.79efg | 57.64bc | 33.56e | 56.36b | 32.61h |
| T8 (OLLS) | 28.63cde | 34.50ef | 50.26bcd | 42.07c | 41.81bcd | 50.01c |
| T9 (Dc) | 14.75g | 66.25a | 36.89d | 57.48a | 32.61d | 61.01a |
| T10 (Fun) | 17.98fg | 58.86b | 44.92cd | 48.22b | 38.73cd | 53.69b |
| T11 (Pc) | 19.02fg | 56.49c | 56.89bc | 34.43d | 42.80bcd | 48.83c |
| T12 (Control) | 43.71**a** | 0.00i | 86.76a | 0.00g | 83.64a | 0.00g |
| LSD (0.05) | 4.26 | 3.23 | 4.68 | 3.85 | 1.65 | 2.85 |
| C.V % | 17.64 | 15.34 | 16.20 | 15.42 | 19.98 | 16.36 |

Where: - **DSLE** = *Datura Stramonium* leaf extract, **ECLE** = *Eucalyptus citriodoria* leaf extract, **JSLE** = *Justicia schimperiana* leaf extract, **RCLE** = *Rucinus communis* leaf extract, **EKRS** = *Echinops kebericho* Rhizome smoke **OEBS** = *Olea Europaea* bark smoke **OELS** = *Olea Europaea* leaf smoke, **OLLS** = *Ocimum lamiifolium* leaf smoke, **DC** = *Difenconazole 25% EC*, **Fun** = *Funguran OH 50 WP*, **PC** = *Propiconazole 25% EC*, **DI** = Disease incidence, **PSI** = Percent Severity Iindex. **CV**= Coefficient of variation; **LSD** = Least significant difference. Means in the column with the same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance.

**Table 5.** Efficacy of fungicides, botanicals and smoke-water on wilt complex disease severity of Hot pepper

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Treatments | **Wilt complex pathogens** | | | | | |
| **Ralstonia** | | **Fusarium** | | **Rhizoctonia** | |
| MeanSI (%) | MeanSI reduction (%) | MeanSI (%) | MeanSI reduction (%) | Mean PSI (%) | MeanSI reduction (%) |
| T1 (DSLE) | 33.33bcd | 38.99de | 37.77bcde | 38.56c | 31.12bcde | 48.15d |
| T2 (ECLE) | 36.10bc | 33.91e | 42.22bc | 31.33e | 33.33bcd | 44.45e |
| T3 (JSLE) | 40.73b | 25.43h | 42.96b | 30.12e | 37.03b | 38.28f |
| T4 (RCLE) | 37.03bc | 32.21ef | 39.26bcd | 36.15c | 34.07bcd | 43.21e |
| T5 (EKRS) | 32.99bcd | 39.60d | 37.03cde | 39.77cd | 30.37cde | 49.39d |
| T6 (OEBS) | 29.63cde | 45.76c | 34.81def | 43.38cd | 28.15def | 53.09c |
| T7 (OELS) | 38.88b | 28.83g | 40.74bc | 33.74cd | 35.56bc | 40.73ef |
| T8 (OLLS) | 37.96b | 30.52ef | 41.48bc | 32.53cd | 34.81bc | 41.98ef |
| T9 (Dc) | 22.22e | 59.32a | 27.41g | 55.42a | 22.22f | 62.96a |
| T10 (Fun) | 26.85de | 50.85b | 31.11fg | 49.40b | 25.92ef | 56.79b |
| T11 (Pc) | 27.78de | 49.15c | 33.33ef | 45.79bc | 26.66ef | 55.56b |
| T12 (Control) | 54.63a | 0.00i | 61.48a | 0.00f | 59.99a | 0.00g |
| LSD (0.05) | 3.74 | 3.15 | 5.67 | 4.28 | 5.96 | 3.24 |
| C.V % | 13.12 | 14.35 | 8.56 | 10.33 | 10.59 | 12.56 |

Where: - **DSLE** = *Datura Stramonium* leaf extract, **ECLE** = *Eucalyptus citriodoria* leaf extract, **JSLE** = *Justicia schimperiana* leaf extract, **RCLE** = *Rucinus communis* leaf extract, **EKRS** = *Echinops kebericho* Rhizome smoke **OEBS** = *Olea Europaea* bark smoke **OELS** = *Olea Europaea* leaf smoke, **OLLS** = *Ocimum lamiifolium* leaf smoke, **DC** = *Difenconazole 25% EC*, **Fun** = *Funguran OH 50 WP*, **PC** = *Propiconazole 25% EC*, **DI** = Disease incidence, **PSI** = Percent Severity Iindex. **CV**= Coefficient of variation; **LSD** = Least significant difference. Means in the column with the same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance.

**Fig.1.** Disease progress curve of Bacterial wilt disease of pepper under different managements.

**Fig. 2.** Disease progress curve of Fusarium wilt disease of pepper under different management treatments.

**Fig. 3.** Disease progress curve of Rhizoctonia root rot disease of pepper under different management treatments.

**3.4 Area under Disease progress Curve (AUDPC)**

The area under the disease progress curve is a very suitable summary of plant disease epidemics that incorporates initial disease severity, the disease rate parameters and the duration of the epidemics, which determines final disease severity. The AUDPC of present study revealed that significant (P< 0.05) differences among treatments had been observed on over all disease development during epidemic period (Fig. 4). The highest disease development in all the three pathogens were seen on the unsprayed plot and the lowest AUDPC values were obtained from the plot treated with *Difenconazole 25% EC* and all the treated treatments show high disease development reduction (Fig.4).

**Fig. 4.** Histogram showing the Area under Disease Progress Curve of Ralstonia solanacearum, Fusarium oxysporum and Rhizoctonia solani under field condition

**3.5 Growth Parameters**

The influence of fungicides, botanical extracts, and smoke-water solutions on the growth parameters of hot pepper exhibited significant differences (P < 0.05), attributable to the reduction in disease development. The treatments notably enhanced plant height, with the tallest plants (68.54 cm) observed in those treated with Difenoconazole 25% EC, statistically comparable to those treated with Funguran OH 50 WP (64.50 cm). Conversely, the control treatment, sprayed with distilled water, resulted in the shortest plant height (33.43 cm). The highest number of leaves (91.39) was found in plots treated with Difenoconazole 25% EC, while the lowest number of leaves (46.50) was recorded in the control plots. Overall, the application of fungicides, botanical extracts, and smoke-water solutions led to improvements in the number of leaves, leaf length, and leaf diameter, attributed to the reduction in disease pressure, thereby facilitating effective photosynthesis.

Among all treatments, Difenoconazole 25% EC resulted in the highest number of primary branches (3.95), while the control plot exhibited the lowest number of primary branches (2.95). However, no statistically significant difference was observed among treatments treated with Datura leaf extract, Eucalyptus leaf extract, and Justicia leaf extract. Additionally, Rucinus leaf extract and Olea Europaea leaf smoke had a similar effect to the control on pepper primary branches, indicating a positive impact and effectiveness of different treatment applications on primary branch formation. The highest number of secondary branches (8.08) was also observed in plots treated with Difenoconazole 25% EC, compared to untreated plot plants (3.96) (Table 6). Furthermore, the application of Difenoconazole 25% EC, Funguran OH 50 WP, Olea Europaea bark smoke, Justicia schimperiana leaf extract, Datura leaf extract, Ocimum lamiifolium leaf smoke, Propiconazole 25% EC, and Eucalyptus leaf extract contributed to improved secondary branch formation. Hence, the application of fungicides, botanicals, and smoke-water solutions positively influenced all vegetative growth parameters of pepper.

In summary, the application of fungicides, plant extracts, and smoke-water solutions significantly improved the growth parameters of pepper, consistent with earlier findings reported by Muthukumar *et al*. (2010), and Telang (2010). The positive effects observed may be attributed to various factors, including the stimulatory and inhibitory effects of botanical extracts on shoot and root elongation and the promotion of seedling growth by smoke-water treatments. Additionally, smoke-water treatments may enhance seedling growth by mobilizing starch reserves and stimulating hydrolytic enzyme activities. Furthermore, smoke-water may serve as a cost-effective stimulus for seedling growth and Vigor in various plant species (Govindaraj *et al*. 2016).

**Table 6**.Effect of fungicides, botanicals and smoke-water on growth parameters of pepper crops

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments | Growth parameters | | | | | | |
| PH (cm) | LN (no.) | LL (cm) | LD (cm) | LA (cm2) | PB (no.) | SB (no.) |
| T1 (DSLE) | 51.67cde | 72.29cd | 8.75abc | 1.24ab | 10.95b | 2.61bc | 5.58bcd |
| T2 (ECLE) | 44.99defg | 61.97def | 7.54bc | 1.04abc | 7.81d | 2.80bc | 5.25bcd |
| T3 (JSLE) | 48.79cdef | 68.71cde | 8.01bc | 0.95bcd | 7.78d | 2.79bc | 5.71bcd |
| T4 (RCLE) | 39.50fgh | 52.04fgh | 6.98bc | 0.73cde | 5.01e | 3.25abc | 4.96cd |
| T5 (EKRS) | 36.30gh | 50.60gh | 7.01bc | 0.61de | 4.28ef | 2.53c | 4.73cd |
| T6 (OEBS) | 58.13bc | 78.88bc | 8.47abc | 1.14ab | 9.29c | 3.92a | 6.63abc |
| T7 (OELS) | 35.96gh | 48.24h | 6.87c | 0.56de | 3.56fg | 2.99abc | 4.87cd |
| T8 (OLLS) | 42.67efgh | 55.07fgh | 7.01bc | 0.64cde | 4.61ef | 3.66ab | 5.54bcd |
| T9 (Dc) | 68.54a | 91.39a | 11.03a | 1.38a | 15.46a | 3.95a | 8.08a |
| T10 (Fun) | 64.50ab | 84.34ab | 9.52ab | 1.20ab | 11.09b | 3.98a | 6.92ab |
| T11 (Pc) | 54.15cd | 60.30efg | 7.68bc | 0.67cde | 4.52ef | 3.62ab | 5.42bcd |
| T12 (Control) | 33.43h | 46.50h | 6.53bc | 0.44e | 2.89g | 2.95abc | 3.96d |
| LSD (0.05) | 1.07 | 1.76 | 2.82 | 0.39 | 1.26 | 1.07 | 1.93 |
| CV% | 12.33 | 9.90 | 21.01 | 26.55 | 10.28 | 19.55 | 20.25 |

**Where:- DSLE** = *Datura Stramonium* leaf extract, **ECLE** = *Eucalyptus citriodoria* leaf extract, **JSLE** = *Justicia schimperiana* leaf extract, **RCLE** = *Rucinus communis* leaf extract, **EKRS** = *Echinops kebericho* Rhizome smoke **OEBS** = *Olea Europaea* bark smoke ,**OELS** = *Olea Europaea* leaf smoke, **OLLS** = *Ocimum lamiifolium* leaf smoke, **DC** = *Difenconazole 25% EC*, **Fun** = *Funguran OH 50 WP*, **PC** = *Propiconazole 25% EC*, **PH =** Plant height, **LN** = Leaf Number, **LL** = Leaf Length, **LD** = Leaf Diameter, **LA** = Leaf Area, **PB** = Primary Branches, **SB** = Secondary Branches, **LSD** = Least significant difference **CV** = Coefficient of variation. Means in the column with the same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance.

**3.6 Yield and Yield Component Parameters**

The impact of fungicides, plant extracts, and smoke-water solutions demonstrated significant differences (P < 0.05) in all yield component parameters and the overall yield of hot pepper. The treatments remarkably improved the number of nodes per plant, number of pods per plant, and marketable pod yield per hectare. The highest yield parameters, including the number of nodes per plant (29.75), number of pods per plant (83.18), and marketable pod yield (23.47 t/ha), were obtained from plots treated with Difenoconazole 25% EC, while the lowest number of nodes per plant (12.43), number of pods per plant (37.57), and marketable yield (10.56 t/ha) were observed in the control treatment, where only distilled water was sprayed.

The application of Definoconazole 25% EC, Funguran OH 50 WP, Olea Europaea bark smoke, Datura leaf extract, Justicia schimperiana leaf extract, and Eucalyptus leaf extract significantly improved the number of nodes per plant (Table 7). Additionally, the mean unmarketable pod yield ranged from 0.29 t/ha to 0.65 t/ha, with the lowest unmarketable pod yield (0.29 t/ha) observed in plots treated with Definoconazole 25% EC and the highest (0.65 t/ha) (Table. 5; Table.7) in the control plots. Moreover, plant extract and smoke-water solution treatments also reduced unmarketable yield compared to the control, indicating a reduction in pod yield loss and unmarketability due to decreased disease development and severity. These findings are consistent with those reported by Abu Khouder *et al*. (2019), suggesting that the increase in fresh pod yield of snap bean and its components may be attributed to enhanced vegetative growth and dry matter accumulation. The vigour in vegetative growth induced by smoke-water treatments likely led to increased photosynthetic and mineral absorption rates, resulting in higher carbohydrate levels in plant tissues, facilitating more cell division and enlargement, ultimately leading to increased pod yield. Additionally, the main active compound in smoke-water solution, butanolide, acts similarly to gibberellins and/or cytokinin, stimulating metabolic processes crucial for photosynthesis activity and the accumulation of metabolites in reproductive organs. Similarly, studies by Kulkarni *et al*. (2010) revealed that smoke water and butanolide increased tomato fruit number and total yield, while onion plants treated with smoke water exhibited significantly higher bulb diameter and bulb weight compared to untreated plants. These findings collectively underscore the positive impact of fungicides, botanicals, and smoke-water solutions in reducing wilt complex disease incidence and severity, resulting in significantly higher yield and yield component parameters compared to the control.

**3.7 Association of Yield, Yield Components, and Disease Parameters**

Correlation analysis between final disease incidence, severity, AUDPC, growth parameters, yield, and yield components under fungicides, botanicals, and smoke-water treatments revealed significant associations (p < 0.05), as shown in Table 8. Impressively the growth parameters, yield components, and yields of pepper exhibited significant (p < 0.05) and strong positive correlations with each other. Conversely, unmarketable pod yield showed significant negative relationships with all growth and yield component parameters (Table 8). Similarly, disease parameters (severity, incidence, and AUDPC) of the three pathogens were significantly and negatively correlated with all growth and yield component parameters except with unmarketable pod yield. This indicates that as the disease incidence and severity increased, the yield and yield attribute parameters decreased, while unmarketable pod yield increased. The reduction in both quantitative yield and quality (market value) of the crop due to disease underscores the importance of disease management strategies. These findings align with previous studies by Sharma *et al*. (2010) and Abraham *et al*. (2017), advocating for the importance of parameters such as number of fruits per plant, fruit weight, number of primary branches, fruit length, fruit diameter, and plant height during the selection process, as these traits directly contribute to yield. Thus, effective disease management strategies are crucial not only for mitigating yield losses but also for preserving the quality and market value of the crop.

**Table 8.** Correlations of plant growth, Yield, yield components and Disease Parameters

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PH | LN | PB | SB | LL | LD | LA | NP | PL | PD | TY | MY | UMY | FocDI | FocPS | RhPDI | RhPSI | RlsPDI | RlsPSI | FAUDP | RAUDPC | RlsAUDPC |
| PH 1\* | 0.36\* | 0.44 | 0.71\* | 0.61\* | 0.72\* | 0.79\* | 0.83\* | 0.77\* | 0.71\* | 0.77\* | 0.78\* | -0.74\* | -0.51\* | -0.57\*\* | -0.53\*\* | -0.56\*\* | -0.60\*\* | -0.58\*\* | -0.58\*\* | -0.56\*\* | -0.55\*\* |
| LN | 1\* | 0.34\* | 0.64\* | 0.69\* | 0.74\* | 0.89\* | 0.82\* | 0.77\* | 0.75\* | 0.76\* | 0.77\* | -0.55\* | -0.55\* | -0.61\* | -0.52\*\* | -0.57\*\* | -0.63\*\* | -0.60\*\* | -0.64\*\* | -0.58\*\* | -0.54\*\* |
| PB |  | 1\* | 0.60\* | 0.03\* | 0.29\* | 0.27\* | 0.31\* | 0.45\* | 0.29\* | 0.29\* | 0.29\* | -0.35\* | -0.25\* | -0.33\* | -0.29\*\* | -0.22\*\* | -0.36\*\* | -0.27\*\* | -0.32\*\* | -0.23\*\* | -0.22\*\* |
| SB |  |  | 1\* | 0.39\* | 0.66\* | 0.68\* | 0.60\* | 0.63\* | 0.59\* | 0.52\* | 0.51\* | -0.43\* | -0.45\* | -0.45\* | -0.43\*\* | -0.45\*\* | -0.45\*\* | -0.46\*\* | -0.44\*\* | -0.46\*\* | -0.40\*\* |
| LL |  |  |  | 1\* | 0.48\* | 0.68\* | 0.48\* | 0.59\* | 0.58\* | 0.59\* | 0.61\* | -0.52\* | -0.36\* | -0.45\* | -0.29\*\* | -0.42\*\* | -0.42\*\* | -0.44\*\* | -0.46\*\* | -0.42\*\* | -0.45\*\* |
| LD |  |  |  |  | 1\* | 0.85\* | 0.82\* | 0.64\* | 0.60\* | 0.67\* | 0.66\* | -0.50\* | -0.37\* | -0.43\* | -0.35\*\* | -0.44\*\* | -0.48\*\* | -0.43\*\* | -0.44\*\* | -0.44\*\* | -0.36\*\* |
| LA |  |  |  |  |  | 1\* | 0.86~~\*~~ | 0.79\* | 0.79\* | 0.81\* | 0.80\* | -0.57\* | -0.54\* | -0.58\* | -0.52\*\* | -0.56\*\* | -0.58\*\* | -0.59\*\* | -0.58\*\* | -0.56\*\* | -0.55\*\* |
| NP |  |  |  |  |  |  | 1\* | 0.78\* | 0.69\* | 0.72\* | 0.70\* | -0.57\* | -0.52\* | -0.57\* | -0.52\*\* | -0.57\*\* | -0.58\*\* | -0.58\*\* | -0.58\*\* | -0.56\*\* | -0.53\*\* |
| PL |  |  |  |  |  |  |  | 1\* | 0.88\* | 0.74\* | 0.75\* | -0.57\* | -0.50\* | -0.60\* | -0.57\*\* | -0.55\*\* | -0.58\*\* | -0.56\*\* | -0.60\*\* | -0.55\*\* | -0.53\*\* |
| PD |  |  |  |  |  |  |  |  | 1\* | 0.79\* | 0.79\* | -0.47\* | -0.55\* | -0.55\* | -0.57\*\* | -0.50\*\* | -0.60\*\* | -0.52\*\* | -0.57\*\* | -0.50\*\* | -0.50\*\* |
| TY |  |  |  |  |  |  |  |  |  | 1\* | 0.99\* | -0.68\* | -0.57\* | -0.72\* | -0.65\*\* | -0.68\*\* | -0.69\*\* | -0.69\*\* | -0.74\*\* | -0.68\*\* | -0.67\*\* |
| MY |  |  |  |  |  |  |  |  |  |  | 1\* | -0.68\* | -0.57\* | -0.71\* | -0.64\*\* | -0.67\*\* | -0.69\*\* | -0.67\*\* | -0.73\*\* | -0.66\*\* | -0.65\*\* |
| UMY |  |  |  |  |  |  |  |  |  |  |  | 1\* | 0.60\* | 0.64\* | 0.53\*\* | 0.65\*\* | 0.65\*\* | 0.59\*\* | 0.64\*\* | 0.65\*\* | 0.57\*\* |
| FocPDI |  |  |  |  |  |  |  |  |  |  |  |  | 1\* | 0.65\* | 0.78\*\* | 0.67\*\* | 0.59\*\* | 0.55\*\* | 0.66\*\* | 0.67\*\* | 0.56\*\* |
| FocPSI |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\* | 0.78\*\* | 0.96\*\* | 0.72\*\* | 0.93\*\* | 0.99\*\* | 0.96\*\* | 0.91\*\* |
| RhPDI |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.81\*\* | 0.64\*\* | 0.77\*\* | 0.78\*\* | 0.81\*\* | 0.77\*\* |
| RhPSI |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.68\*\* | 0.95\*\* | 0.95\*\* | 0.99\*\* | 0.93\*\* |
| RlsPDI |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.67\*\* | 0.74\*\* | 0.68\*\* | 0.63\*\* |
| RlsPSI |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.92\*\* | 0.95\*\* | 0.98\*\* |
| FAUDPC |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.95\*\* | 0.90\*\* |
| RAUDP |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* | 0.93\*\* |
| RlsAUD |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1\*\* |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Where: **PH** = Plant height, **LN** = Leaf number, **PB** = Primary branch, **SB** = Secondary branch, **LL** = Leaf length, LD = Leaf diameter, **LA** = Leaf area, **NN** = Number of node, **NP** = number of Pod, **PL** = Pod length, **PD** = Pod diameter, **TY** = Total yield, **MY** = Marketable yield, **UMY** = Unmarketable yield, **FocPDI** = Percent disease incidence of Fusarium oxysporum, **FocPSI** = Percent disease severity of Fusarium oxysporum, **RhPDI** = Percent disease incidence of Rhizoctonia, **RhPSI** = Percent disease severity of Rhizoctonia, **RlsPDI** = Percent disease incidence of Ralstonia, **RlsPSI** = Percent disease severity of Ralstonia, **FAUDPC** = Area under disease progress curve of Fusarium oxysporum, **RAUDPC** = Area under disease progress curve of Rhizoctonia, **RlsAUDPC** = Area under disease progress curve of Ralstonia. \* means significant \*\* strong correlation or highly significant.

**Conclusions**

Hot pepper stands as an important vegetable crop in Ethiopia, serving as a primary source of income for numerous smallholder farmers across the country. However, the substantial yield losses attributed to complex diseases caused by fungal and bacterial pathogens pose a significant challenge to both the quality and quantity of hot pepper production. Despite previous management efforts yielding limited success, our study sought to address this research gap by evaluating various management strategies for hot pepper wilt disease complex. Our findings underscore the efficacy of Difenoconazole 25% EC, Funguran OH 50 WP, and Propiconazole 25% EC in significantly reducing wilt disease incidence and severity in hot pepper. Moreover, the tested plant extracts and smoke water solutions exhibited promising antifungal and antibacterial properties, effectively slowing down pathogen infection and mitigating disease impact. Specifically, chemical fungicide treatments led to outstanding reductions in wilt disease incidence, ranging from 48.83% to 61.01% for Rhizoctonia, 34.34% to 57.48% for Fusarium, and 56.49% to 66.25% for Ralstonia, compared to untreated controls. Similarly, plant extract and smoke water solution treatments demonstrated substantial disease incidence reductions of 13.87% to 45% for Ralstonia, 27.82% to 47.83% for Fusarium, and 32.61% to 50.01% for Rhizoctonia. Furthermore, our study revealed significant improvements in marketable yield, ranging from 47.57% for Olea Europaea bark smoke solution to 56.33% for Difenoconazole 25% EC treatment, highlighting the practical efficacy of these management interventions. In conclusion, our research affirms the efficacy of tested commercial fungicides, plant extracts, and smoke water solutions in controlling pepper wilt complex diseases in field conditions. Difenoconazole 25% EC and Funguran WP 50% emerge as particularly effective remedies for managing wilt complex diseases in pepper. Additionally, plant extracts and smoke water solutions offer viable alternative management tools for combating the tested pathogens and associated diseases in hot pepper. Nevertheless, further studies are used to explore the development and commercialization of plant extracts and smoke water solutions, identifying more efficient formulation types. Additionally, investigations into the shelf life, frequency, and application rates of plant extracts and smoke water solutions are recommended for optimizing their efficacy in disease management protocols.

**Data Availability**

Data is available in the manuscript.

**Author Contributions**

All authors actively contributed to this paper's formulation, discussion of findings, and composition, collectively assuming responsibility for its content.

**Conflict of Interest**

The authors do not have any possible conflicts of interest.

**Funding Sources**

There is no funding source.

**Acknowledgment**

The authors express their gratitude to Ambo University and Ambo Agricultural Research Center for providing access to research fields and laboratory facilities for conducting this study.

**Ethics Approval**

Not applicable

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