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Effect of Combining Plant Extracts on *Fusarium* Wilt (*Fusarium oxysporum* f.sp. *lycopersici*) in Tomato

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ABSTRACT

Background and Objective: Tomato production is significantly impacted by *Fusarium* wilt, a disease caused by *Fusarium oxysporum* f.sp. *lycopersici*. Traditional chemical controls for this disease often face limitations, prompting the exploration of plant-based alternatives. This study evaluates the effectiveness of neem leaves, bamboo leaves, and rice husk extracts, individually and in combination, against *Fusarium* wilt. **Materials and Methods:** The study, conducted at I.A.R and T. Obafemi Awolowo University, Ibadan in 2022, tested plant extracts at 2.47, 7.29, and 12.90% concentrations for pathogen inhibition. A 2×3 factorial design was used for the screenhouse trial; 50 mL was applied per treatment. The tomato variety was arranged in a Randomized Complete Block Design with three replications. Data collected on disease incidence and severity with the agronomic traits were subjected to Analysis of Variance and means of significant treatments were separated using Duncan's Multiple Range Test at $p<0.05$. **Results:** It showed all treatments inhibited pathogen growth, with neem leaf extract being the most effective (0.94 cm), followed by neem and rice husk (0.78 cm). The chemical control had 0.30 cm growth at 12.90% concentration. In the screen house trial, bamboo leaf extract was most effective in reducing disease impact *in vitro*, but the combined treatments had no significant effect on plant growth. The Ibadan local tomato variety responded best to individual neem and bamboo leaf extracts with improved plant height, flowers, and fruit production. **Conclusion:** The study concludes that neem and bamboo leaf extracts, when used separately, can effectively control *Fusarium* wilt both in laboratory and field conditions.

KEYWORDS

Fusarium wilt, tomato production, neem leaf extract, bamboo leaf extract, rice husk, plant-based alternatives, disease control

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most significant vegetable crops globally with origination from Western South America. It is valued for its diverse characteristics, including fleshy fruits, sympodia (main axes or stem made up of successive secondary axes), and compound leaves-features that distinguish

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it from other model plants like rice that belongs to the *Solanaceae* family, tomato is closely related to commercially important plants such as eggplant, pepper, and tobacco[1]. In Nigeria, tomato ranks as one of the most crucial vegetable crops, second only to potato and sweet potato globally in production, yet it tops the list of canned vegetables. The crop is highly adaptable, thriving in warm conditions with optimal temperatures of 20-25°C during the day and 15-17°C at night[2]. Tomato cultivation requires about 600 mm of well-distributed moisture throughout the growing season, a light loam soil with high organic content, and a pH range of 5-7.5[3]. The dry season in the Nigerian Savanna, characterized by cooler weather and minimal pest and disease incidence, is the best period for tomato growth[4]. Tomato is not only a staple in Nigerian diets but also an essential cash crop for both small and large-scale farmers. It is a rich source of vitamins A, C, and E, and minerals that are vital for human health, offering protection against various diseases[5]. The crop also plays a significant role in poverty reduction by providing employment and income, particularly for smallholder farmers[6]. Despite its importance, tomato production faces several challenges, particularly from pests and diseases. Among the most problematic diseases is *Fusarium* wilt, caused by *Fusarium oxysporum* f.sp. *lycopersici*, a soil-borne pathogen capable of persisting in the soil for years without a host[7]. The use of synthetic fungicides to control *Fusarium* wilt has raised concerns due to their potential toxicity to humans and animals, as well as their negative impact on the environment and agroecosystem. Additionally, the high cost, technical requirements, and limited availability of these chemicals to smallholder farmers further complicate their use. In response to these challenges, there is growing interest in developing environmentally friendly and sustainable agricultural practices. One such approach is the use of botanical fungicides derived from plant extracts. These natural products, rich in secondary metabolites like phenolic acid, caffeic acid, chlorogenic acid, and scopoletin, have demonstrated antimicrobial properties and offer safer, more economical alternatives to synthetic chemicals[8] also the indiscriminate use of pesticides has also over time resulted in the build-up of resistance among target pathogens considering this severe problem this research work was therefore aimed to evaluate the effectiveness of combining plant extracts-specifically neem leaves (*Azadirachta indica*), bamboo leaves (*Bambusa vulgaris*), and rice husk (*Oryza sativa*)-in controlling the growth of *Fusarium oxysporum* f.sp. *lycopersici* in tomato plants. The potential of these botanicals to serve as a sustainable and accessible option for tomato farmers was assessed, to recommend effective, eco-friendly control measures against *Fusarium* wilt in tomato production.

MATERIALS AND METHODS

The experiment was carried out at the Institute of Agricultural Research and Training (I.A.R. & T.), Moor Plantation, Ibadan during the cropping season of April to August, 2022 which is located on Latitude 07°23´N, Longitude 03°51´E, and altitude 650m in the humid zone of the rainforest belt of Southwestern Nigeria with a mean annual rainfall of 1220 mm and mean temperature of 26°C. High temperatures and plenty of sunshine generally prevail during the dry season.

Sources of plant samples: The botanicals used in this study were 950 g of neem leaves (Azadirachta indica), 800 g bamboo leaves (*Bambusa vulgaris*), and 900 g of rice husk (*Oryza sativa*). *Azadirachta indica* and *Bambusa vulgaris* were collected from the farm of the Federal College of Agriculture, Moor Plantation, Apata, Ibadan. *Oryza sativa* (husk) was collected from a local rice farmer.

Glassware's sterilization: All glassware and equipment used in the experiment were thoroughly washed with detergent, rinsed with distilled water, and allowed to air dry. The glass Petri dishes were wrapped in aluminum foil and sterilized in a Gallen Kamp hot air oven at 160°C for 3 hrs. Metal wares, conical flasks, and beakers were similarly covered with aluminum foil and sterilized.

Inoculating chamber preparation: The inoculating chamber was sterilized by swabbing with cotton wool dipped in methylated spirit (ethanol with 10% methanol). After swabbing, the ultraviolet (UV) light was turned on for one hour before and after use to prevent contamination. The incubator was sterilized by swabbing with cotton wool dipped in methylated spirit and set to a room temperature of 27°C.

Agar preparation: Potato dextrose agar (PDA) was prepared by weighing 39.5 g of PDA powder into a 1000 mL sterilized conical flask. Distilled water (1000 mL) was added, and the mixture was agitated to dissolve the powder. The flask was covered with non-absorbent cotton wool wrapped in aluminum foil. The mixture was heated in a hot water bath for 15 min to ensure complete dissolution. The PDA was then sterilized in an autoclave (Astell Benchtop Autoclave 2012, Astell Scientific London, United Kingdom) at 121°C (1.05 kg/cm^2) for 15 min. After cooling, 1.25 g of streptomycin powder was added per litre of PDA to create an antibacterial medium. The PDA was aseptically poured into sterile Petri dishes (approximately 15 mL per dish) and allowed to solidify.

Isolation of *Fusarium oxysporum* f.sp. *lycopersici*: About 400 g of Infected tomato leaves were collected from farmers' fields and brought to the laboratory. The leaves were cut into pieces, rinsed in five changes of distilled water containing 2% hypochlorite, and dried on sterile paper towels. The dried leaves were inoculated onto PDA in Petri dishes and later sub-cultured to obtain pure cultures of the pathogen and some were later stained for pathogen identification.

Aqueous crude extraction of plant materials: The plant materials Rice (*Oryza sativa*) husk, Neem (*Azadirachta indica*) leaves, and Bamboo (*Bambusa vulgaris*) leaves were rinsed separately with clean water, air-dried until crispy, and then ground into powder using a blender. (Samsung power blender RB-035M813 South Korea) Distilled water (250 mL) was used as the solvent for extracting the botanicals at different weights (30, 60, and 90 g) in separate beakers. The beakers were covered with aluminum foil to prevent contamination and left for 24 hrs to maximize the release of active ingredients. The solutions were filtered twice: First through clean muslin cloths, and then through filter paper in a sterile environment.

Procedural application of botanicals in laboratory experiment: Before pouring the PDA into Petri dishes, 1.25 g of streptomycin powder was added per litre of PDA to create an antibacterial medium. The PDA was then poured (10 mL) into 9 cm Petri dishes. Various concentrations of the combined extracts (2.4, 7.2, and 12.0%) were added to the PDA and swirled for even dispersion. After solidification, 5 mm diameter discs of *Fusarium oxysporum* were cut from a 7-day-old culture using a flame-sterilized cork borer and aseptically transferred to the center of the cooled PDA in the Petri dishes using a flame-sterilized inoculating needle. The Petri dishes were then incubated, and mycelial growth was measured after 24 hrs using perpendicular lines drawn on the bottom of the dishes.

Experimental layout in the laboratory and screen house: A 2×3 factorial experiment was conducted to investigate the effect of different plant extracts on the growth of *Fusarium oxysporum* f.sp. *lycopersici*. The experiment was laid out in a Completely Randomized Design (CRD) with three replications. The fungicide Benomyl (50% active ingredient, trade name Benlate) was used as a chemical control. A solution of 0.5 g Benlate powder in 1 L of sterile distilled water served as the control.

Investigation of the effect of botanicals on *Fusarium oxysporum* f.sp. *lycopersici*: Petri dishes were marked with two perpendicular lines passing through the center and incubated at 28°C for 7 days. The interaction between the pathogen and the combined extracts at different concentrations was observed and recorded. Statistical analysis was performed using SAS ANOVA with means separated by Tukey's test at $p \leq 0.05$ procedure of SAS 9.0[9] to test for significant differences among treatments.

Experimental methodology: The screenhouse experiment was conducted at the Institute of Agricultural Research and Training (I.A.R. & T.), Ibadan. Tomato seeds of three varieties (Ibadan local, Roman VF, and Rio) were obtained from the National Horticultural Research Institute (NIHORT), Ibadan. The target pathogen was obtained from previously isolated stock culture. Soil collected from uncultivated land was

sterilized at 270°C using the hot air method to destroy any unwanted organisms. The soil was allowed to cool before filling into trays for nursery planting of the tomato seeds at 10 kg of sterile soil per tray. The three tomato varieties were planted in separate trays filled with sterile topsoil. Agronomic practices were carried out as at when due. Seedlings were transplanted at 3 weeks after planting into pots containing 10 kg of sterile soil each, with 3 seedlings per pot, later thinned to 2 seedlings per pot. The pots were arranged 30 by 30 cm apart according to variety and treatment in a Completely Randomized Design (CRD).

The pathogen (*Fusarium oxysporum* f.sp. *lycopersici*) was inoculated by adding 5 mL of a spore suspension (5.65×10 spores) to 10 kg of sterilized soil at 3 weeks after transplanting. The botanical extracts were applied at a concentration of 36.00% (25 mL each of neem leaves and bamboo leaves, neem leaves and rice husk, or rice husk and bamboo leaves, totaling 50 mL per treatment). Control treatments included 50 mL of each extract and control with only the pathogen. The extracts were applied by spraying at 4 weeks after transplanting, timed to coincide with the onset of pathogen symptoms. Observations on plant height, number of leaves, stem girth, disease incidence, and number of fruits were recorded at 7-day intervals. Collected data were analyzed, and disease severity was determined.

The percentage of disease incidence (DI) was calculated using the formula below[10]:

$$\text{Disease incidence (\%)} = \frac{\text{Number of infected plants}}{\text{Total number of healthy and infected plants}} \times 100$$

The disease severity was scored using an adopted scale, 0 to 5[11]:

Score	Symptoms
0	No symptoms
1	Very small necrotic lesion on leaves
2	Light necrosis covering less than 40% of the leaf area
3	Moderate necrosis on leaves, 40-60% of the leaf area
4	Severe necrosis on 60-80% of the leaf area
5	Very severe necrosis on more than 90% of the leaf area, or dead plants

The number of leaves was accessed by counting and recording the number of leaves of each tagged plant per plot.

The plant height was determined by measuring the plant stand from the soil level to the apex using a meter rule.

The number of leaves, flowers, and fruits was recorded by measuring the length and width of the longest leaf from each tagged plant in each plot using a meter rule. Stem girth was measured with a vernier caliper placed around the stems of the tagged plants, and the readings were recorded. At harvest, the fresh weight of the produce from each plot was weighed with a kitchen scale (Bosch KGV100 Germany) and the results were documented.

RESULTS

Effect of plant extracts on mycelial growth of *Fusarium* wilt pathogen (*Fusarium oxysporum* f.sp. *lycopersici*) obtained from diseased plant at 1 day After inoculation: The effect of various plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* 1 day after inoculation (Table 1 and Plate 1). The analysis of the data revealed significant differences ($p \leq 0.05$) among the treatments at different concentrations. The treatments involving neem leaves extract, chemical control (Benlate), rice husk, neem leaves+bamboo leaves, and rice husk+bamboo leaves (CHEM, B, A, AC, BC) exhibited the least mycelial growth, with values ranging from 0.30 to 0.33 cm at 1 mL concentration.

Plate 1: Sample of tomato plant infected with *Fusarium oxysprum* f.sp. *lycopersici*

Table 1: Effect of plant extracts on mycelia growth (cm) of *Fusarium* wilt pathogen of tomato (*Fusarium oxysporum* f.sp. *lycopersici*) at 1 day after inoculation

Treatment	1 mL	3 mL	5 mL
AB	0.43^{b}	0.36^{bc}	0.33^{b}
AC	0.41^{b}	0.38^{bc}	0.28^{c}
BC	0.33^{b}	0.39^{c}	0.30^{c}
A	0.30^{b}	0.30^{d}	0.35^{b}
B	0.33^{b}	0.38^{bc}	0.38^{b}
C	0.40^{b}	0.35^{b}	0.30^{c}
TFU	0.71^{b}	0.71^{a}	0.71^{a}
CHEM	0.30^{b}	0.30^{d}	0.30^{b}

Means in the same column with different letters are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

The bamboo leaves extract alone (C) and the combination of neem leaves+rice husk (AB) showed slightly higher growth, with values of 0.40 and 0.43 cm, respectively. The pathogen control (TFU) demonstrated the highest mycelial growth at 0.71 cm, indicating no inhibition by the treatment. At 3 mL concentration (7.2%), the neem leaves extract (A) and chemical control (CHEM) were most effective, with mycelial growth values of 0.30 cm. Other treatments, including bamboo leaves, rice husk, neem+bamboo, neem+rice husk, and rice husk+bamboo (C, B, AC, AB, BC), exhibited slightly higher growth, with values between 0.35 and 0.39 cm. The pathogen control (TFU) again showed the highest growth at 0.71 cm. Also, at 5 mL concentration (12.0%), the treatment combinations of neem+bamboo, rice husk+bamboo, bamboo only, and chemical control (AC, BC, C, CHEM) demonstrated a significant reduction in pathogen growth, with values of 0.28 to 0.33 cm. Neem+rice husk and neem only (AB, A) showed slightly higher growth inhibition with values of 0.33 and 0.35 cm, respectively. The pathogen control (TFU) continued to exhibit the highest mycelial growth at 0.71 cm and across all concentrations, the chemical control (Benlate) and neem-based treatments (alone or in combination) consistently inhibited the growth of *Fusarium* wilt pathogen more effectively than other treatments. The pathogen control (TFU) consistently showed the highest growth, indicating the effectiveness of the plant extracts in reducing pathogen proliferation.

Effect of plant extracts on mycelial growth of *Fusarium* wilt pathogen (*Fusarium oxysporum* f.sp. *lycopersici*) at 2 days after inoculation: The effects of various plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* at 2 days after inoculation (Table 2). The values obtained revealed significant differences ($p<0.05$) among treatments at different concentrations. The treatments with neem leaves+rice husk extract (AB) showed slightly higher mycelial growth inhibition at 0.53 cm, compared to the neem leaves+bamboo leaves extract (AC), which had a growth value of 0.46 cm (1 mL concentration 2.4%).

Table 2: Effect of plant extracts on mycelia growth (cm) of *Fusarium* wilts pathogen of tomato (*Fusarium oxysporum* f.sp. *lycopersici*) at 2 days after inoculation

Treatment	1 mL	3 mL	5 mL
AB	0.53^{b}	0.41^{bc}	0.41^{b}
AC	0.46^{b}	0.38^{bc}	0.36^{b}
BC	0.36^{c}	0.35^{c}	0.38^{b}
A	0.35^{c}	0.45^{c}	0.30^{b}
B	0.36^{c}	0.35^{c}	0.36^{b}
C	0.33^{c}	0.75^{b}	0.33^{b}
TFU	1.03^{a}	1.03^{a}	1.03^{a}
CHEM	0.30^{c}	0.30^{c}	0.30^{b}

Means in the same column with different alphabets are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

The combination of rice husk+bamboo leaves (BC) and the chemical control (CHEM) exhibited lower growth at 0.36 and 0.30 cm, respectively. Treatments with neem only, rice husk only, and bamboo leaves only (A, B, C) resulted in similar mycelial growth values ranging from 0.33 to 0.36 cm. The pathogen control (TFU) demonstrated the highest mycelial growth at 1.03 cm, indicating no inhibition by any treatment.

At 3 mL concentration (7.2%), the neem leaves extract (A) and neem+rice husk extract (AB) were most effective in reducing mycelial growth, with values of 0.30 and 0.41 cm, respectively. Treatments with neem+bamboo, rice husk+bamboo, and rice husk only (AC, BC, B) exhibited slightly higher growth values, ranging from 0.35 to 0.38 cm.

The bamboo leaves only (C) showed a higher growth value at 0.75 cm, indicating less effectiveness. while in the pathogen control (TFU) showed the highest growth at 1.03 cm.

The 5 mL concentration (12.0%), the neem+rice husk extract (AB), and neem+bamboo leaves extract (AC) showed consistent inhibition of mycelial growth, with values of 0.41 and 0.36 cm, respectively. The chemical control (CHEM) and neem extract (A) showed equal effectiveness at 0.30 cm. The other treatments, including rice husk+bamboo, bamboo only, and rice husk only (BC, C, B), had similar growth values between 0.30 and 0.38 cm however the pathogen control (TFU) continued to have the highest mycelial growth at 1.03 cm, confirming the efficacy of the plant extracts in reducing the pathogen's growth and across all concentrations, the chemical control (Benlate) and neem-based treatments (alone or in combination) consistently inhibited the growth of the *Fusarium* wilt pathogen more effectively than other treatments. The pathogen control (TFU) consistently showed the highest growth.

Effect of plant extracts on mycelial growth of *Fusarium* wilt pathogen (*Fusarium oxysporum* f.sp. *lycopersici*) at 3 days after inoculation: The effect of plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* 3 days after inoculation (Table 3) revealed significant differences among the treatments across different concentrations. The chemical control (CHEM) demonstrated the most significant reduction in mycelial growth with a value of 0.30 cm at 1 mL concentration (2.4%). The neem leaves+rice husk extract (AB) and neem leaves only (A) showed moderate pathogen growth inhibition, with values of 0.68 and 0.65 cm, respectively. However, neem+bamboo leaves (AC), rice husk+bamboo leaves (BC), and bamboo only (C) had mycelial growth values ranging from 0.42 to 0.60 cm while the pathogen control (TFU) exhibited the highest mycelial growth at 1.22 cm, these indicated no inhibition by the treatments but at 3 mL concentration (7.2%), the chemical control (CHEM) and combinations of neem+rice husk, neem+bamboo, and rice husk+bamboo (AB, AC, BC) were the most effective, with pathogen growth values all at approximately 0.30 cm. However, the bamboo leaves only (C) showed less efficacy with a growth value of 0.81 cm, but the pathogen control (TFU) consistently showed the highest growth at 1.22 cm.

Table 3: Impact of plant extracts on mycelial growth of *Fusarium* wilt in tomatoes after 3 days

Treatment	1 mL	3 mL	5 mL
AB	0.68^{ab}	0.40^{c}	0.70^{b}
AC	0.49^{c}	0.40^{c}	0.30^{c}
BC	0.42^{abc}	0.32^{c}	0.33^{c}
A	0.65^{abc}	0.50^{c}	0.65^{c}
B	0.42^{abc}	0.38^{c}	0.33^{c}
C	0.60^{abc}	0.81^{b}	0.30^{c}
TFU	1.22^{a}	1.22^{a}	1.22^{a}
CHEM	0.30^{d}	0.30^{c}	0.30^{c}

Means in the same column with different alphabets are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

Table 4: Effect of plant extracts on mycelial growth of *Fusarium* wilt in tomatoes after 4 days

Treatment	1 mL	3 mL	5 mL
AB	0.61^{b}	0.40^{ab}	0.58^{b}
AC	0.53b^{c}	0.38^{ab}	0.33^{b}
BC	0.40^{b}	0.32^{c}	0.33^{c}
A	0.53^{b}	0.78^{ab}	0.73^{b}
B	0.40^{b}	0.43^{ab}	0.35^{b}
C	0.53^{b}	0.30^{b}	0.30^{b}
TFU	1.40^{a}	0.78^{a}	1.40^{a}
CHEM	0.30^{b}	0.30^{b}	0.30^{b}

Means in the same column with different alphabets are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

At 5 mL concentration (12%), the chemical control (CHEM) along with neem+bamboo leaves (AC), rice husk+bamboo leaves (BC), neem leaves only (A), bamboo only (C), and rice husk only (B) showed the lowest growth values, all at or near 0.30 cm but the neem+rice husk extract (AB) showed slightly higher pathogen growth at 0.70 cm. The pathogen control (TFU) consistently had the highest growth at 1.22 cm, showing the effectiveness of the treatments in reducing pathogen proliferation. Thus, the chemical control (CHEM) consistently exhibited the greatest reduction in mycelial growth across all concentrations. Among the plant extracts, the combination treatments (AB, AC, BC) were generally more effective than individual extracts, though all treatments significantly reduced the pathogen growth compared to the control 1.

The effect of plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* at 4 days after inoculation (Table 4) showed varying degrees of pathogen inhibition across different concentrations hence at 1 mL concentration (2.4%) all the treatments except for the pathogen control (TFU), demonstrated similar levels of pathogen inhibition. The chemical control (CHEM) and bamboo extract (C) showed the least pathogen growth, both recording 0.30 cm. The neem+rice husk (AB) and neem+bamboo (AC) treatments also exhibited reduced growth, with values of 0.61 cm and 0.53 cm, respectively with the pathogen control (TFU) that gave the highest mycelial growth at 1.40 cm, indicating no inhibitory effect.

And at 3 mL concentration (7.2%) the chemical control (CHEM) and bamboo extract (C) again showed the least pathogen growth, both with values of 0.30 cm. The neem+rice husk (AB) and rice husk only (B) treatments had moderate pathogen inhibition, with values of 0.40 and 0.43 cm, respectively. But the pathogen control (TFU) still had the highest growth at 0.78 cm.

The 5 mL concentration (12%) results showed that all treatments were statistically ($p \leq 0.05$) similar in reducing pathogen growth, with the chemical control (CHEM), bamboo (C), rice husk (B), neem+ bamboo (AC), and rice husk+bamboo (BC) treatments exhibiting the least growth, all at or near 0.30 cm

Table 5: Effect of plant extracts on mycelial growth of *Fusarium* wilt in tomatoes after 5 days

Treatment	1 mL	3 mL	5 mL
AB	0.63^{b}	0.60^{b}	0.80^{b}
AC	0.66^{c}	0.43^{b}	0.30^{b}
BC	0.45^{b}	0.47^{b}	0.35^{b}
A	0.45^{b}	0.38^{b}	0.55^{b}
B	0.45^{b}	0.38^{b}	0.35^{b}
C	0.55^{b}	0.90^{b}	0.28^{b}
TFU	1.49^{a}	1.49^{a}	1.49^{a}
CHEM	0.30^{b}	0.30^{b}	0.30^{b}

Means in the same column with different alphabets are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

but neem only (A) and neem+rice husk (AB) had slightly higher pathogen growth values of 0.73 and 0.58 cm, respectively with the pathogen control (TFU) showed the highest growth at 1.40 cm in a consistent manner. The chemical control (CHEM) consistently demonstrated the greatest reduction in mycelial growth across all concentrations. Among the plant extracts, bamboo (C) and its combinations with neem and rice husk (AC and BC) were generally more effective at inhibiting pathogen growth than other treatments. However, the pathogen control (TFU) consistently exhibited the highest growth.

Effect of plant extracts on mycelial growth of *Fusarium* wilt pathogen (*Fusarium oxysporum* f.sp. *lycopersici*) at 5 days after inoculation: The effect of plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* at 5 days after inoculation was analyzed, and the results (Table 5) indicated that while there were no significant differences ($p<0.05$) among the treatments, the pathogen control (TFU) exhibited the highest level of mycelial growth across all concentrations (1, 3, 5 mL). At 1 mL concentration (2.4%). The mycelial growth was generally inhibited across all treatments compared to the pathogen control. The chemical control (CHEM) and rice husk extract (B) had the lowest pathogen growth, both at 0.30 cm, followed by the neem+rice husk (AB) treatment at 0.63 cm. but at 3 mL concentration (7.2%) the chemical control (CHEM) continued to show the least pathogen growth at 0.30 cm. The bamboo extract (C) showed a higher growth rate of 0.90 cm compared to other treatments, while neem+rice husk (AB) and neem leaves only (A) treatments had moderate pathogen growth, with values of 0.60 and 0.38 cm, respectively, also at 5 mL concentration (12.0%) the chemical control (CHEM), bamboo extract (C), and combinations of neem with other extracts (AC, BC) exhibited the least pathogen growth, with values of 0.30 to 0.35 cm while the neem+rice husk (AB) and neem only (A) treatments showed moderate pathogen growth, recording values of 0.80 and 0.55 cm, respectively. The pathogen control (TFU) consistently showed the highest growth at 1.49 cm across all concentrations, indicating the effectiveness of the treatments in reducing the growth of the pathogen. In other words, the chemical control (CHEM) was consistently the most effective at inhibiting mycelial growth across all concentrations, the plant extracts, particularly those containing neem and rice husk (AB, AC, BC), also demonstrated significant inhibitory effects on the pathogen, albeit to a lesser extent.

The effect of various plant extracts on the mycelial growth of *Fusarium oxysporum* f.sp. *lycopersici* at 6 days (Table 6) after inoculation. The analysis revealed no significant differences ($p<0.05$) among the treatments, except for the pathogen control (TFU), which consistently exhibited the highest level of pathogen growth across all concentrations (1, 3, and 5 mL). At 1 mL concentration (2.4%) the lowest pathogen growth was observed in the chemical control (CHEM) and neem only (A) treatments, both at 0.30 cm, followed by the rice husk+bamboo (BC) treatment at 0.38 cm. The neem+rice husk (AB) and bamboo only (C) treatments showed slightly higher pathogen growth, with values of 0.65 and 0.62 cm, respectively and the 3 mL concentration (7.2%) the chemical control (CHEM) maintained the lowest pathogen growth at 0.30 cm. The bamboo only (C) treatment exhibited the highest pathogen growth

Table 6: Effect of plant extracts on mycelial growth of *Fusarium* wilt in tomatoes after 6 days

Treatments	1 mL	3 mL	5 mL
AB	0.65^{b}	0.48^{a}	0.78^{a}
AC	0.64^{a}	0.58^{a}	0.35^{a}
BC	0.38^{a}	0.33^{a}	0.30^{a}
A	0.30^{a}	0.80^{a}	0.94^{a}
B	0.38^{a}	0.35^{a}	0.40^{a}
C	0.62^{a}	0.93^{a}	0.28^{a}
TFU	2.45^{a}	2.45^{a}	2.47^{b}
CHEM	0.30^{a}	0.30^{a}	0.30^{a}

Means in the same column with different alphabets are significantly different ($p \leq 0.05$) according to Duncan's multiple range tests, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, BC: Aqueous extract rice husk and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract rice husk only, C: Aqueous extract of bamboo leaves only, CHEM: Chemical control (Benlate) and TFU: Pathogen only

Table 7: Effect of plant extract application on plant height of tomato (cm)

Treatment	3 WAP	6 WAP	9 WAP	12 WAP
ABV1	23.70^{cdefg}	55.00^{abcdef}	71.00^{bcd}	52.00^{fgh}
ABV2	30.00^{bc}	40.00^{defgh}	50.00^{ef}	62.00^{def}
ABV3	18.30^{efg}	36.00^{fgh}	48.00^{ef}	62.50^{def}
ACVI	29.00^{bcd}	41.50^{defgh}	50.00^{ef}	59.00^{efg}
ACV2	17.40^{fg}	45.00^{cdefg}	56.00^{de}	40.00^{hi}
ACV3	20.45^{cdefgh}	37.50^{efgh}	56.00^{de}	45.00^{gh}
BCV1	15.15^{g}	25.00^{gh}	33.00^{fg}	28.50^{ij}
BCV2	17.35^{fg}	35.00^{fgh}	42.50^{efg}	27.00^{ij}
BCV3	25.25^{cdef}	41.00^{defgh}	55.00^{de}	54.50^{fg}
AV1	27.50^{cde}	60.00^{abcd}	82.^{50abcc}	80.00^{bc}
AV2	39.75^{a}	67.00^{ab}	80.00^{abc}	80.00^{bc}
AV3	37.00^{ab}	58.00^{abcde}	85.00^{abc}	75.00^{cd}
BV1	25.50^{cdef}	55.50^{abcdef}	76.00^{abc}	72.50^{cde}
V2	25.55^{cdef}	66.00^{abc}	68.50^{cd}	70.00^{cde}
BV3	29.45^{bcd}	63.50^{abc}	72.50^{abcd}	70.00^{cde}
CV1	16.20^{fg}	52.00^{bcdef}	88.50^{ab}	90.00^{ab}
CV2	27.60^{cde}	73.50^{a}	89.50^{a}	96.00^{a}
CV3	20.10^{defg}	52.00^{bcdef}	72.50^{abcd}	70.00^{cde}
VIDIS	17.50^{fg}	23.00^{h}	28.50^{g}	25.00^{j}
V2DIS	22.90^{cdefg}	34.50^{fgh}	47.50^{ef}	48.50^{gh}
V3DIS	23.50^{cdefg}	37.00^{efgh}	45.00^{efg}	54.54^{fg}

Means in the same column with different alphabet are significantly different ($p \leq 0.05$) according to Duncan's Multiple range test, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract of rice husk, C: Aqueous extract of bamboo leaves only, V1: Ibadan local, V2: Roman Vf, V3: Rio, DIS: Disease and WAP: Weeks after planting

among the plant extracts at 0.93 cm, while neem+rice husk (AB) and neem only (A) treatments had moderate pathogen growth with values of 0.48 and 0.80 cm, respectively while at 5 mL concentration (12.0%) the chemical control (CHEM) and rice husk+bamboo (BC) treatments had the lowest pathogen growth, both at 0.30 cm. The neem+rice husk (AB) treatment showed slightly higher pathogen growth at 0.78 cm, followed by neem only (A) at 0.94 cm. The pathogen control (TFU) consistently displayed the highest pathogen growth, with a value of 2.47 cm. The chemical control (CHEM) and the combination treatments (AC, BC) were the most effective in reducing the growth of *Fusarium oxysporum* f.sp. *lycopersici*. The plant extracts, particularly those containing neem and rice husk, demonstrated moderate inhibitory effects on the pathogen. The pathogen control (TFU) consistently had the highest level of mycelial growth, indicating the effectiveness of the treatments in inhibiting the growth of the pathogen in the petri dishes.

Effect of plant extracts on plant height (cm) of tomato (*Solanum lycopersicum*): The impact of various plant extracts on tomato plant height measured at 3, 6, 9, and 12 weeks after planting (WAP) (Table 7). The analysis shows significant differences in plant height based on the treatments and varieties

Table 8: Effect of plant extract application on disease severity of tomato plants

Treatment	6 WAP	9 WAP	12 WAP
ABV1	2.00^{ab}	2.00^{cd}	2.00^{b}
ABV2	1.00^{b}	2.00^{cd}	5.00^{a}
ABV3	1.00^{b}	3.00^{bc}	1.00^{c}
ACVI	2.00^{ab}	1.00^{d}	2.00^{b}
ACV2	1.50^{ab}	4.00^{ab}	1.00^{c}
ACV3	1.00^{b}	4.50^{a}	1.00^{c}
BCV1	2.00^{ab}	2.00^{cd}	1.00^{c}
BCV2	2.50^{ab}	3.00^{bc}	1.00^{c}
BCV3	1.50^{ab}	1.50^{d}	5.00^{a}
AV1	1.00^{b}	1.00^{d}	1.00^{c}
AV2	1.00^{b}	4.00^{ab}	4.50^{a}
AV3	1.50^{ab}	1.00^{d}	5.00^{a}
BV1	1.50^{ab}	2.00^{cd}	1.50^{bc}
BV2	2.00^{ab}	2.00^{cd}	1.50^{bc}
BV3	1.50^{ab}	2.00^{cd}	1.00^{c}
CV1	2.50^{ab}	2.00^{cd}	1.00^{c}
CV2	1.00^{b}	1.50^{d}	5.00^{a}
CV3	1.00^{b}	1.50^{d}	5.00^{a}
VIDIS	3.00^{a}	2.00^{cd}	1.00^{c}
V2DIS	2.00^{ab}	2.00^{cd}	5.00^{a}
V3DIS	2.00^{ab}	1.00^{d}	5.00^{a}

Means in the same column with different alphabet are significantly different ($p \leq 0.05$) according to Duncan's Multiple range test, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract of rice husk, C: Aqueous extract of bamboo leaves only, V1: Ibadan local, V2: Roman Vf, V3: Rio, DIS: Disease and WAP: Weeks after planting

used at three weeks after planting (3 WAP). The highest plant heights were observed in the treatments with neem+rice husk (AB) for Ibadan local (V1) and Roman Vf (V2), with heights of 23.70 and 30.00 cm, respectively while the lowest heights were recorded in the rice husk+bamboo (BC) treatment, especially for Ibadan local (V1) and Roman Vf (V2), with heights of 15.15 and 17.35 cm, respectively. At six weeks after planting (6 WAP) the Roman Vf (V2) treated with neem+bamboo (AC) showed the highest growth at 73.50 cm, followed closely by Rio (V3) with neem+rice husk (AB) at 66.00 cm while the lowest heights were found in the disease control (DIS) treatment, particularly for Roman Vf (V2) at 34.50 cm at Nine weeks after planting (9 WAP). The Roman Vf (V2) with neem+bamboo (AC) had the highest height at 89.50 cm, with Rio (V3) under neem only (A) also showing significant growth at 85.00 cm while the smallest heights were observed in the disease control (DIS) treatments, with Roman Vf (V2) at 47.50 cm while at twelve weeks after planting (12 WAP). The Roman Vf (V2) showed the highest height at 96.00 cm, followed by Rio (V3) with neem+rice husk (AB) at 80.00 cm with the disease control (DIS) treatment recorded the least growth with Roman Vf (V2) at 48.50 cm. Hence, the treatments with Neem, particularly when combined with rice husk (AB) or bamboo (AC), generally resulted in higher plant heights. The lowest plant heights were consistently observed in the disease control (DIS) treatment across all varieties. The height of plants increased over time, with a slight decrease in height after 9 weeks, except for treatments with bamboo only, which maintained higher growth.

The impact of various plant extracts on disease severity in tomato plants at 6, 9, and 12 weeks after planting (WAP) (Table 8) The analysis reveals significant differences ($p<0.05$) among the treatments and across the measurement weeks at six weeks after planting (6 WAP). The treatments with neem+rice husk (AB) on Ibadan local (V1) and neem only (A) on Roman Vf (V2) showed the lowest disease severity, with scores of 2.00 and 1.00, respectively. The disease control (DIS) had a higher severity score of 3.00, indicating more severe disease but at nine weeks after planting (9 WAP). The highest disease severity was observed in treatments with neem+rice husk (AB) on Roman Vf (V2) and rice husk+bamboo (BC) on Rio (V3), both showed the scores of 5.00. the treatments with neem only (A) on Ibadan local (V1) and neem+bamboo (AC) on Roman Vf (V2) had lower severity scores of 1.00 and 4.00, respectively and on

Table 9: Effect of plant extract application on number of leaves of tomato (cm)

Treatment	6 WAP	7 WAP	8 WAP	9 WAP	10 WAP	11 WAP
ABV1	3.00^{def}	2.00^{ef}	2.50^{efg}	7.00^{ab}	3.00^{bc}	0.00^{d}
ABV2	1.50^{fg}	2.50^{def}	1.50^{fg}	1.50^{cd}	2.00^{c}	0.00^{d}
ABV3	0.00^{g}	3.00^{cde}	2.50^{efg}	2.50^{bcd}	1.50^{c}	0.00^{d}
ACVI	5.00^{e}	5.50^{bc}	5.50^{cd}	3.50^{bcd}	3.50^{bc}	0.00^{d}
ACV2	2.50^{ef}	4.00^{cde}	5.50^{cd}	5.00^{bc}	2.50^{bc}	1.00^{bc}
ACV3	5.00^{d}	5.00^{bcd}	5.00^{de}	4.50^{bcd}	3.50^{bc}	1.50^{bc}
BCV1	0.00^{g}	0.00^{f}	0.00^{g}	0.00^{d}	0.00^{c}	0.00^{d}
BCV2	0.00^{g}	1.50^{ef}	0.00^{g}	0.00^{d}	0.00^{c}	0.00^{d}
BCV3	3.00^{def}	3.50^{cde}	3.00^{def}	5.00^{bc}	0.00^{c}	0.00^{d}
AV1	11.00^{b}	12.00^{a}	11.00^{b}	10.50^{a}	10.00^{a}	4.00^{a}
AV2	8.00^{c}	7.50^{b}	7.50^{c}	3.50^{a}	3.50^{bc}	0.00^{d}
AV3	32.50^{a}	12.50^{a}	14.00^{a}	11.00^{a}	9.00^{a}	2.50^{b}
BV1	1.50^{fg}	3.00^{cde}	3.00^{def}	0.00^{d}	0.00^{c}	0.00^{d}
BV2	1.50^{fg}	4.00^{cde}	4.50^{de}	0.00^{d}	0.00^{c}	0.00^{d}
BV3	0.00^{g}	2.00^{ef}	3.00^{def}	0.00^{d}	0.00^{c}	0.00^{d}
CV1	4.00^{de}	2.00^{ef}	2.50^{efg}	6.00^{bc}	10.00^{a}	4.50^{a}
CV2	3.50^{def}	4.00^{cde}	3.50^{def}	5.00^{bc}	5.50^{b}	1.00^{cd}
CV3	2.50^{ef}	1.50^{ef}	2.50^{egf}	2.00^{cd}	3.50^{bc}	0.00^{d}
VIDIS	0.00^{g}	0.00^{f}	0.00^{g}	0.00^{d}	0.00^{c}	0.00^{d}
V2DIS	0.00^{g}	0.00^{f}	0.00^{g}	0.00^{d}	0.50^{c}	0.00^{d}
V3DIS	0.00^{g}	0.00^{f}	0.00^{g}	0.00^{d}	1.00^{c}	0.00^{d}

Means in the same column with different alphabet are significantly different ($p \leq 0.05$) according to Duncan's Multiple range test, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract of rice husk, C: Aqueous extract of bamboo leaves only, V1: Ibadan local, V2: Roman Vf, V3: Rio, DIS: Disease and WAP: Weeks after planting

twelve weeks after planting (12 WAP) The treatments with neem+rice husk (AB) on Ibadan local (V1), rice husk+bamboo (BC) on Roman Vf (V2), and neem only (A) on Ibadan local (V1) showed the lowest disease severity scores of 1.00. The highest severity was noted in treatments with neem+rice husk (AB) on Rio (V3) and rice husk+bamboo (BC) on Roman Vf (V2) with scores of 5.00. Hence, the disease severity increased over the weeks for varieties with higher leaf counts, specifically Roman Vf (V2) and Rio (V3). The severity remained constant at 1.00 for Neem only (A) across the weeks. The disease typically progressed from older to newer leaves, eventually affecting all leaves of the plant (Plate 1).

Effect of plant extracts on number of flowers in tomato varieties: The effect of various plant extracts on the number of flowers in tomato plants from 6 to 11 weeks after planting (WAP) (Table 9). The data indicated that the number of flowers increased at 6 WAP but began to decline by 9 WAP, at six weeks after planting (6 WAP). The highest number of flowers was recorded in treatments with neem only on Ibadan local (AV1) and Rio (AV3), with 11.00 and 32.50 flowers, respectively. while the other treatments that included neem only on Roman Vf (AV2) and bamboo only on Ibadan local (CV1) had 8.00 and 4.00 flowers, respectively while at nine weeks after planting (9 WAP). The number of flowers decreased significantly for most treatments. Neem only on Ibadan local (AV1) and Rio (AV3) still had the highest counts of 10.50 and 11.00 flowers, respectively. In contrast the treatments with neem+rice husk and bamboo only, such as ABV1 and BCV3, showed lower counts of 7.00 and 5.00 flowers, respectively. The number of flowers further declined twelve weeks after planting (12 WAP) in most treatments. Neem only on Ibadan local (AV1) and Rio (AV3) had the highest counts remaining at 4.00 and 2.50 flowers, respectively. With treatments that had the pathogen only (VIDIS, V2DIS, V3DIS) showed no flowers from 6 to 10 weeks, and there were minimal counts of 0.50 and 1.00 flowers in varieties Roman Vf (V2) and Rio (V3) by 10 WAP, respectively thus the treatments with single plant extracts generally performed better in maintaining flower counts compared to combined treatments. The presence of disease significantly impacted flowering, leading to a gradual decline in flower numbers as the disease progressed.

Table 10: Effect of plant extract application on number of fruit of tomato plants

Treatment	8 WAP	9 WAP
ABV1	0.00^{c}	0.00^{c}
ABV2	0.00^{c}	0.00^{c}
ABV3	0.00^{c}	0.00^{c}
ACVI	0.00^{c}	0.00^{c}
ACV2	0.00^{c}	0.00^{c}
ACV3	0.00^{c}	0.00^{c}
BCV1	0.00^{c}	0.00^{c}
BCV2	0.00^{c}	0.00^{c}
BCV3	0.00^{c}	0.00^{c}
AV1	3.50^{a}	2.50^{a}
AV2	0.00^{c}	2.00^{b}
AV3	0.00^{c}	0.00^{c}
BV1	0.00^{c}	0.00^{c}
BV2	0.00^{c}	0.00^{c}
BV3	0.00^{c}	0.00^{c}
CV1	1.00^{b}	2.00^{b}
CV2	0.00^{c}	0.00^{c}
CV3	0.00^{c}	0.00^{c}
VIDIS	0.00^{c}	0.00^{c}
V2DIS	0.00^{c}	0.00^{c}
V3DIS	0.00^{c}	0.00^{c}

Means in the same column with different alphabet are significantly different ($p \leq 0.05$) according to Duncan's Multiple range test, AB: Aqueous extract of neem leaves and rice husk, AC: Aqueous extract of neem leaves and bamboo leaves, A: Aqueous extract of neem leaves only, B: Aqueous extract of rice husk, C: Aqueous extract of bamboo leaves only, V1: Ibadan local, V2: Roman Vf, V3: Rio, DIS: Disease and WAP: Weeks after planting

The effect of plant extracts on the number of fruits produced by tomato plants at 8 and 9 weeks after planting (WAP) (Table 10). The eight weeks after planting (8 WAP). The highest number of fruits was observed with the treatment of neem leaves only on Ibadan local (AV1), which produced 3.50 fruits while the bamboo leaves only on Ibadan local (CV1) had a moderate performance with 1.00 fruit. While all the other treatments that had neem leaves combined with rice husk, bamboo, and rice husk alone, showed no fruit production. But for nine weeks after planting (9 WAP), the neem leaves only on Ibadan local (AV1) continued to lead with 2.50 fruits. The treatment with bamboo leaves only on Ibadan local (CV1) had 2.00 fruits. The effect of neem leaves only on Roman Vf (AV2) showed an improvement from 0.00 fruits at 8 WAP to 2.00 fruits at 9 WAP, and thus, the other treatments that included combined plant extracts and the pathogen treatments, reported no fruit production therefore, the results indicated that single treatments with neem leaves or bamboo leaves on Ibadan local were more effective in the promotion of fruit production when compared to other treatments since most treatments especially those combined with pathogens did not produce fruits at either time point.

DISCUSSION

In this research work, sustainable alternatives to chemical fungicides to manage *Fusarium* wilt in tomato plants were explored, neem leaves (*Azadirachta indica*), bamboo leaves (*Bambusa vulgaris*), and rice husk (*Oryza sativa*) were used for the control of *Fusarium oxysporum* f.sp. *lycopersici* in tomato plants. The pathogen mycelium was consistently reduced and the highest growth record was documented, thus, the effectiveness of the plant extracts in the reduction of pathogen proliferation. The experiment was in tandem with earlier research carried out on *Fusarium oxysporum* f.sp. *lycopersici* as a major pathogen affecting tomato crop production[12]. While, chemical controls have traditionally increased crop productivity and quality, their indiscriminate use poses risks to human and animal health and can lead to environmental contamination[13]. In response to these concerns, alternative control methods, such as plant

extracts, have gained attention. Plant extracts are natural sources of antimicrobial substances that are generally considered safe, degrade naturally, and do not pose significant health or environmental risks[14]. This study demonstrated that neem leaf extracts effectively inhibited the growth of *Fusarium oxysporum* in both laboratory and screenhouse conditions. The low incidence of *Fusarium* wilt in tomato plants treated with neem leaves can be attributed to the presence of compounds such as gedunin and azadirachtin, which possess antifungal properties[15]. Gedunin is a tetranortriterpenoid with known antifungal properties when exuded, inhibits Fusarium growth[16] while azadirachtin also contributes to the inhibition of fungal growth. Similarly, bamboo leaf extracts also exhibited inhibitory effects against the pathogen. The bamboo leaf extract had the inhibitory effect that raised its potency to sporulating mycelial growth in both the laboratory and screen house trial[17]. The reduced incidence of *Fusarium* wilt in plants treated with bamboo leaves is likely due to various active compounds such as flavonoids, glycosides, phenolic acids, coumarin lactones, anthraquinones, and amino acids[18,19]. This possible combination of plant extracts in the laboratory has a promising antibiotic potency which could be harnessed into effective biopesticide in the reduction of *Fusarium* disease in economic crops which also corroborated the work of Alzohairy[20]. The success of plant extract combinations in laboratory settings suggests a controlled environment minimizes external variables such as rainfall, sunlight, and temperature[21,22]. However, the efficacy of these combinations in the screen house was compromised, possibly due to climatic factors or insufficient concentrations of the plant extracts[23]. This ineffectiveness can be resolved due to the photoperiod that plant metabolites and phytochemicals act best as reported by Zhang *et al*.[23] at some antimicrobial phytochemicals act best at some photoperiod where sunlight penetrates and activates some chemicals in plants[24].

A limitation of this study is the variability in the efficacy of plant extracts under different environmental conditions, which may affect reproducibility. Additionally, the exact mode of action of these extracts against *Fusarium oxysporum* remains unclear. Future research should focus on optimizing extract concentrations, evaluating their long-term effects on soil microbiota, and exploring their integration with other biocontrol strategies for sustainable disease management.

CONCLUSION

This research-work explored sustainable alternatives to chemical fungicides for the management of *Fusarium* wilt in tomatoes, caused by *Fusarium oxysporum* f.sp. *lycopersici*. The plant extracts from neem leaves, bamboo leaves, and rice husk were evaluated. Neem leaf extract showed the most effective pathogen inhibition, followed by bamboo. These eco-friendly and cost-effective plant-based solutions improved tomato yield and quality, and this offers a viable option for smallholder farmers. Hence, further field studies should optimize plant extract concentrations and test their efficacy across varying environmental conditions in different agroecological areas.

SIGNIFICANCE STATEMENT

This study explored sustainable alternatives to chemical fungicides to manage *Fusarium* wilt in tomatoes, a global challenge caused by *Fusarium oxysporum* f.sp. *lycopersici*. Chemical controls are often costly, environmentally harmful, and inaccessible to smallholder farmers in developing countries. By the evaluation of neem and bamboo leaf extracts, along with rice husk, the research identified eco-friendly, cost-effective, and locally available solutions. The results indicated that these plant extracts significantly reduced *Fusarium* wilt with enhanced tomato yield and quality. This approach not only supported food security and income generation for smallholder farmers but also aligned with the global shift towards sustainable agriculture. The study has laid a foundation for future research on optimization of plant-based disease management techniques.

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