



## Integrated Management of Fusarium-Induced Dry Rot in Sweet Potato Using Indigenous Plant Extracts and Rhizospheric Antagonists

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### Research Article

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### ABSTRACT

Sweet potato (*Ipomoea batatas* L.) production in Nigeria is severely limited by *Fusarium*-induced dry rot. This study evaluated the integrated management of *Fusarium* spp. using indigenous plant extracts and rhizospheric microorganisms. A survey of 100 farmlands in Ogun State identified *Fusarium* as the predominant pathogen, accounting for 61.2% of isolates. Quantitative phytochemical screening of six indigenous plants revealed that *Zingiber officinale* contained the highest concentrations of alkaloids, saponins, and phenols. *In vitro* assays showed that 20% *Z. officinale* ethanol extract inhibited mycelial growth by over 70%. Furthermore, *Trichoderma* and *Bacillus* species isolated from the rhizosphere demonstrated significant antagonistic activity; with one of the *Trichoderma* isolate achieving 71.7% inhibition. Field and storage trials confirmed that integrated application reduced disease incidence and improved plant vigour (length of stem and number of leaves). These results suggest that combining *Z. officinale* extracts with biocontrol agents offers a sustainable, eco-friendly alternative to chemical fungicides.



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**Keywords:** *Fusarium* sp., Phytochemicals, Rhizospheric microorganisms, Sweet potato

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## 1. Introduction

Sweet potato (*Ipomoea batatas* L.) is a vital staple crop in Nigeria, providing essential nutrients and contributing significantly to food security [1]. However, its production is threatened by various pathogens, notably *Fusarium solani*, which causes root rot and stem canker, leading to substantial yield losses [2]. In South Korea, for instance, *F. solani* has been identified as a primary agent of root rot in sweet potatoes, characterized by circular lesions with dark and light brown concentric rings and internal cavities in the roots [3]. Similarly, in Egypt, *Fusarium oxysporum* f. sp. *batatas* has been reported to cause Fusarium wilt in sweet potato, affecting various genotypes [4].

Traditional management strategies often rely on chemical fungicides, which can be costly and pose environmental and health risks [5]. Moreover, the effectiveness of these fungicides can diminish over time due to the development of resistant fungal strains. For example, in the northeastern United States, *Fusarium sambucinum* developed resistance to benzimidazole fungicides, leading to increased losses from dry rot in potatoes [6]. This scenario underscores the need for alternative, sustainable disease management strategies that are both effective and environmentally friendly.

One promising approach involves the use of plant-based extracts with inherent antifungal properties [7-8]. Studies have demonstrated the efficacy of various plant extracts against *Fusarium* sp. For instance, *Momordica charantia* seed extract has shown significant inhibitory

effects on *Fusarium* sp., effectively reducing mycelial growth [9]. Additionally, certain rhizospheric microorganisms exhibit antagonistic activities against soil-borne pathogens, offering potential as biocontrol agents. The rhizosphere serves as a microbial seed bank where microorganisms transform organic and inorganic substances into accessible plant nutrients, thereby enhancing plant health [10].

Integrating these plant extracts and beneficial microbes could provide a holistic approach to managing *Fusarium*-induced diseases in sweet potatoes [7-8]. This integrated strategy not only targets the pathogen directly but also promotes a healthier soil microbiome, which can enhance plant resilience against various stresses. This study aims to evaluate the combined efficacy of selected indigenous plant extracts and rhizospheric microorganisms in controlling *Fusarium* associated with dry rot disease of sweet potato in Ogun State, Nigeria. By exploring these sustainable alternatives, the research seeks to enhance sweet potato production while minimizing reliance on chemical fungicides.

## 2. Methods

### 2.1. Sample Collection

A comprehensive survey was conducted across 100 farmlands within the 20 Local Government Areas of Ogun State, Nigeria. Both healthy and diseased sweet potato (*Ipomoea batatas* L.) tubers were collected from each

farmland. Additionally, rhizospheric soil samples were obtained from the root zones of these plants to isolate potential antagonistic microorganisms. Six indigenous plants—*Terminalia superba*, *Momordica charantia*, *Garcinia kola*, *Zingiber officinale*, *Alchornea cordifolia*, and *Annona muricata*—were also obtained from the surveyed locations for their potential antifungal properties.

## 2.2. Isolation and Identification of *Fusarium* Species

Isolation of *Fusarium* species from diseased sweet potato tubers was performed using standard mycological techniques. Infected tuber tissues were surface-sterilised with 70% ethanol, rinsed in sterile distilled water, and aseptically excised into small pieces. These pieces were plated onto Potato Dextrose Agar (PDA) supplemented with 50 mg/L streptomycin to inhibit bacterial growth and incubated at 25 °C for 5–7 days. Emerging fungal colonies were sub-cultured to obtain pure isolates. Morphological characterisation was carried out following *The Fusarium Laboratory Manual* [11], focusing on colony morphology and micro-/macroconidia characteristics. For instance, isolates grown on PDA were observed for colony reverse colour. Some *Fusarium* isolates produced cream, blue, or dark brown pigments, but notably, they did not produce the purple/violet pigments typical of certain other *Fusarium* species. In addition, Carnation Leaf Agar (CLA) was used to induce more stable conidiogenous structures. A key feature observed in some isolates was the production of microconidia on distinctively long monophialides (conidiophores with a single opening). Growth rate testing was also performed by measuring radial growth on PDA at 25 °C. The isolates were generally fast-growing, reaching a diameter of 90 mm within 5–9 days, which helped differentiate them from slower-growing *Fusarium* species. Because species-level identification was based solely on morphological and biochemical characteristics without molecular confirmation, all isolates are reported at the genus level only (as *Fusarium* sp. or *Fusarium* spp.).

## 2.3. Identification of Associated Mycoflora

Other fungal species isolated from the diseased sweet potato tubers were identified using cultural and morphological characteristics. Pure cultures were observed for colony colour, texture, and growth patterns on PDA. Microscopic examination was performed using the teased-mount technique with Lactophenol Cotton Blue (LPCB) stain. Diagnostic features, including the presence of septate or aseptate hyphae, conidiophore structure, and the shape and arrangement of conidia/spores, were compared with standard mycological keys by [12].

## 2.4. Isolation of Rhizospheric Microorganisms

Rhizospheric soil samples were used to isolate fungi and bacteria with potential antagonistic activity against

*Fusarium* sp. Serial dilutions of soil suspensions were plated onto PDA for fungi and Nutrient Agar (NA) for bacteria. Plates were incubated at 28°C for 5–7 days. Distinct colonies were selected and purified through repeated sub-culturing. Fungal isolates were identified morphologically, while bacterial isolates were characterized using Gram staining and biochemical tests as described by Toppo and colleagues [13]. As stated above, because molecular confirmation was not performed and identification relied solely on morphological and biochemical characterisation, all isolates are reported only at the genus level. Consequently, individual isolates of the same genus are distinguished by arbitrary numbers (e.g., *Trichoderma* sp. 1, *Trichoderma* sp. 2). These numbers are for laboratory tracking only and do not imply species-level distinction.

## 2.5. Preparation of Plant Extracts

Fresh plant materials were washed, air-dried at room temperature, and ground into fine powders. Aqueous extracts were prepared by soaking 100 g of each powder in 500 mL of distilled water for 24 hours, followed by filtration through Whatman No. 1 filter paper. Ethanol extracts were obtained by macerating 100 g of each powder in 500 mL of 95% ethanol for 72 hours, with occasional shaking, and then filtering as described above. Filtrates were concentrated under reduced pressure using a rotary evaporator at 40°C and stored at 4°C until use.

## 2.6. Phytochemical Screening and Quantification

Quantitative analyses were performed using spectrophotometric methods [14]. Alkaloids were determined via the Bromocresol Green (BCG) method using a caffeine standard curve (absorbance at 470 nm). Saponins were quantified using the vanillin-sulfuric acid assay with absorbance read at 544 nm against a saponin standard. Total phenols were assessed using the Folin-Ciocalteu reagent method; the reaction mixture was incubated for 90 minutes before measuring absorbance at 765 nm, expressed as Gallic Acid Equivalents (GAE). Cardiac glycosides were evaluated using the Baljet reagent with absorbance read at 495 nm.

## 2.7. Pathogenicity Test

The pathogenicity of 25 *Fusarium* isolates (from Locations A to Y) was evaluated. The pathogenicity of the *Fusarium* isolates was confirmed using Koch's postulates. Healthy sweet potato tubers were surface-sterilised and wounded with a sterile needle. A 5 mm mycelial disc from a 7-day-old *Fusarium* culture was placed onto each wound site, and the inoculated areas were sealed with sterile parafilm. Healthy tubers treated with sterile PDA discs were maintained as controls for

each set of inoculations. Tubers were incubated at 25 °C and 90% relative humidity for 14 days. Development of rot symptoms was recorded, and *Fusarium* was re-isolated from symptomatic tissues to fulfil Koch's postulates. Disease severity was quantified using a Disease Severity Index (DSI) based on a 0–5 mm scale of rot progression. Isolates were categorised based on virulence: Avirulent, Low virulent, Moderately virulent, Virulent, and Strongly virulent. Control tubers were inoculated with sterile PDA discs to ensure no symptoms developed in the absence of the pathogen.

### 2.8. *In vitro* Antifungal Assay

The efficacy of plant extracts against *Fusarium* sp. was evaluated using the poisoned food method. Sterile PDA was amended with each extract to achieve concentrations of 5%, 10%, 15%, and 20% (v/v) before solidification [15]. A 5 mm mycelial disc of *Fusarium* sp. was placed at the center of each plate. Control plates contained PDA without extracts. All plates were incubated at 25°C for 7 days. Radial mycelial growth was measured daily, and the percentage inhibition of mycelial growth (PIMG) was calculated using the formula:

$$\text{PIMG (\%)} = \left( \frac{R1 - R2}{R1} \right) \times 100$$

Where:

R1 is the radial growth in the control plate.

R2 is the radial growth of in the treatment).

### 2.9. Antagonistic Activity of Rhizospheric Microorganisms

The rhizospheric microorganisms were identified using a combination of morphological and biochemical characterisation. Fungal antagonists (*Trichoderma* spp.) were identified based on colony appearance, mycelial structure, and conidial characteristics under light microscopy, following the keys of [12]. Bacterial antagonists (*Bacillus* spp.) were identified through Gram staining and biochemical tests, including catalase, starch hydrolysis, and citrate utilisation assays. The antagonism assay was conducted using the dual culture technique on Potato Dextrose Agar (PDA). A 5 mm disc of the pathogen (*Fusarium* sp.) was placed 2 cm from the edge of the plate, and a similar disc of the antagonist was placed on the opposite side. The plates were incubated at 28 ± 2 °C for a duration of 120 hours (5 days). The inhibitory activity was measured by calculating the percentage growth inhibition (PGI) using the formula.

$$\text{PGI (\%)} = \left( \frac{R1 - R2}{R1} \right) \times 100$$

Where:

R1 is the radial growth of *Fusarium* sp. in the control plate.

R2 is the radial growth of *Fusarium* sp. in the dual culture (interfacing with the antagonist).

### 2.10. Field and Storage Trials

Field trials were established to evaluate the practical efficacy of the treatments. The experimental layout included six groups: three concentrations of *Zingiber officinale* ethanol extract (12%, 15%, and 20%), an inoculated control, an ethanol control, and a non-inoculated control. Plant vigour was assessed by measuring the Length of Stem (LOS) and counting the Number of Leaves (NOL) at 3, 6, 9, and 12 days post-inoculation during the 6th and 7th weeks of growth. Harvested tubers were subjected to storage trials under ambient conditions (28 ± 2 °C) for four weeks to determine the rate of rot development and the potential for these treatments to prolong shelf life.

### 2.11. Statistical Analysis

Data were analyzed using One-way Analysis of Variance (ANOVA) via SPSS (Version 25.0). Means were compared at a 95% confidence level ( $p < 0.05$ ). Where significant differences were observed, mean separation was performed using Duncan's Multiple Range Test (DMRT).

## 3. Results

### 3.1. Prevalence of Fungi Isolated from Diseased Potato Tubers

From the diseased sweet potato tubers, a total of 45 fungal isolates were obtained. The most frequently isolated genus was *Fusarium*, with three distinct morphotypes accounting for 61.2%, 38.7%, and 37.0% of isolates, respectively. Other fungi included *Aspergillus* spp. (up to 35%), *Rhizopus* spp. (30.2%), and *Penicillium* spp. (up to 33.3%). The high prevalence of *Fusarium* spp. suggests its significant role in sweet potato dry rot in Ogun State.

### 3.2. Isolation of Rhizospheric Microorganisms

Rhizospheric soil samples yielded 20 fungal and 10 bacterial isolates. The fungal genera identified included *Trichoderma*, *Penicillium*, and *Aspergillus*, while bacterial isolates belonged to genera such as *Bacillus* and *Pseudomonas*. These microorganisms are known for their antagonistic properties against various plant pathogens.

### 3.3. Phytochemical Composition of Plant Extracts

Phytochemical analysis of the six indigenous plants revealed the presence of bioactive compounds with potential antifungal properties. The quantitative phytochemical distribution varied significantly across species. *Zingiber officinale* demonstrated the highest concentration of alkaloids (0.7305 g/mL) and cardiac glycosides (0.5235 g/mL), which correlates with its superior antifungal efficacy. In contrast, *Momordica charantia* exhibited the minimum alkaloid content (0.3195 g/mL), while *Annona muricata* contained the lowest saponin levels (0.0459 g/mL). These compounds are recognised for their antimicrobial activities, which may contribute to inhibiting *Fusarium* sp..

Table 1. Quantitative analysis of phytochemical constituents in selected plants

Phytochemicals (g/mL)	Ts	Mc	Zo	Gc	Ac	Am
Alkaloids	0.6795	0.3195	0.7305	0.5500	0.4240	0.3335
Flavonoids	0.0000	0.0000	0.0088	0.0067	0.0030	0.0205
Saponin	0.7905	0.3800	0.8165	0.6330	0.5020	0.0459
Phenol	0.1250	0.1035	0.1605	0.1440	0.1135	0.1270
Cardiac Glycosides	0.3425	0.1555	0.5235	0.4545	0.2680	0.1690

KEY: Ts- *Terminalia superba*, Mc- *Momodica charantia*, Zo- *Zingiber officinale*, Gc- *Garcinia cola*, Ac- *Alchornea cordifolia*, and Am- *Annona muricata*.

### 3.4. Pathogenicity Assessment

Pathogenicity tests confirmed that the *Fusarium* isolates induced characteristic dry rot symptoms in healthy sweet potato tubers. Inoculated tubers developed circular lesions with dark and light

brown concentric rings and internal cavities, consistent with previous reports of *Fusarium*-induced root rot and stem canker in sweet potatoes (Table 2). Control tubers remained symptom-free, fulfilling Koch's postulates and confirming *Fusarium* as the causative agent.

Table 2. Pathogenicity of different isolates of *Fusarium* on healthy tubers

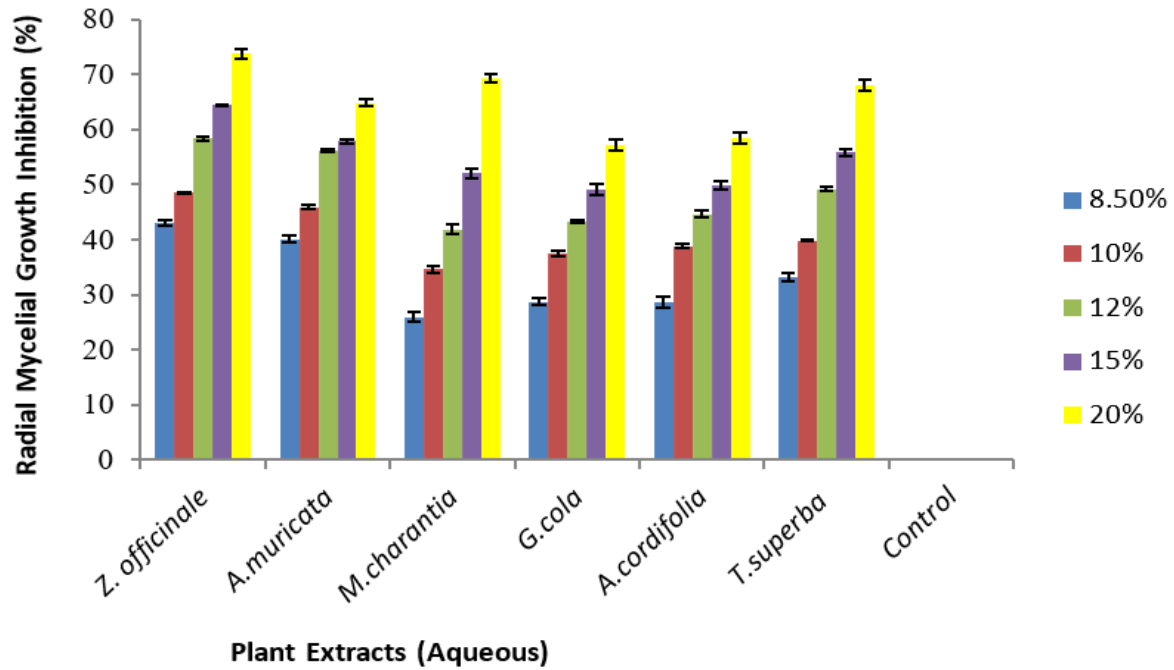
Isolates	Disease Severity Index (DSI) 0 – 5 (mm)				
	Avirulent	Low virulent	Moderately virulent	Virulent	Strongly virulent
Location A	–	–	–	3.25	–
Location B	–	–	2.70	–	–
Location C	–	–	–	3.20	–
Location D	–	–	2.50	–	–
Location E	–	1.50	–	–	–
Location F	–	1.30	–	–	–
Location G	–	–	–	3.25	–
Location H	–	–	–	3.50	–
Location I	–	–	–	3.30	–
Location J	–	–	–	3.15	–
Location K	–	–	–	–	4.10
Location L	–	–	–	3.70	–
Location M	–	–	–	–	4.50
Location N	–	–	–	–	4.70
Location O	–	–	–	3.50	–
Location P	–	–	2.40	–	–
Location Q	–	–	2.50	–	–
Location R	–	–	2.15	–	–
Location S	–	–	–	3.70	–
Location T	–	–	–	–	4.20
Location U	–	–	–	–	4.70
Location V	–	–	2.30	–	–
Location W	–	–	–	3.25	–
Location X	–	–	–	3.40	–
Location Y	–	–	–	–	4.15

KEY: Locations A to Y depicts 25 different farm sites

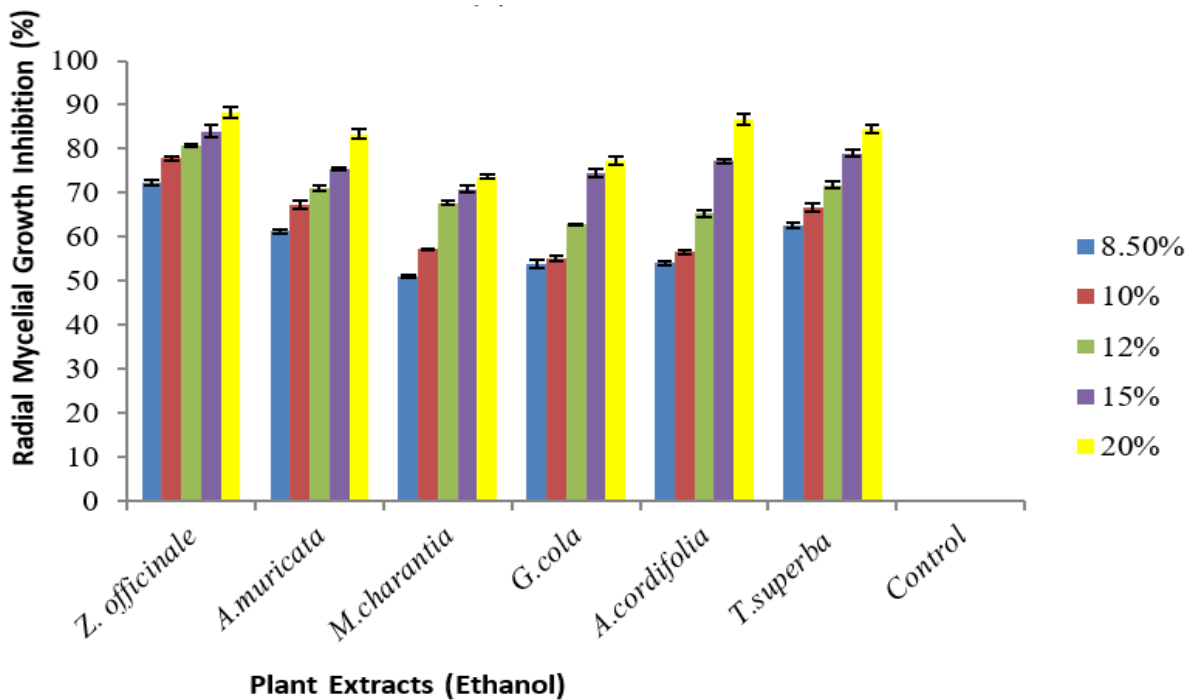
### 3.5. In vitro Antifungal Efficacy of Plant Extracts

The antifungal activity of aqueous and ethanol extracts from the six plants was evaluated against *F. solani* using the poisoned food method. *Zingiber officinale* extracts demonstrated the most significant inhibitory effect, with

a concentration of 20% resulting in over 70% inhibition of mycelial growth (Figure 1a, b; Figure 2). This aligns with studies highlighting the antifungal properties of plant-derived compounds against *Fusarium* sp.



(a)



(b)

Figure 1. Percentage inhibition of radial mycelial growth after 120 hours of inoculation in aqueous and ethanol extracts

**3.6. Antagonistic Potential of Rhizospheric Microorganisms**

In dual culture assays, all tested rhizospheric microorganisms exhibited antagonistic activity against *Fusarium* sp. (Table 3; Figure 3). Fungal isolates, particularly those from the genus *Trichoderma*, inhibited mycelial growth by more than

67%. *Trichoderma* species are known for their mycoparasitic behaviour, producing enzymes and secondary metabolites that degrade pathogenic fungi. Bacterial isolates, especially those from the genus *Bacillus*, also displayed significant inhibition, likely due to the production of antifungal compounds and competition for nutrients.

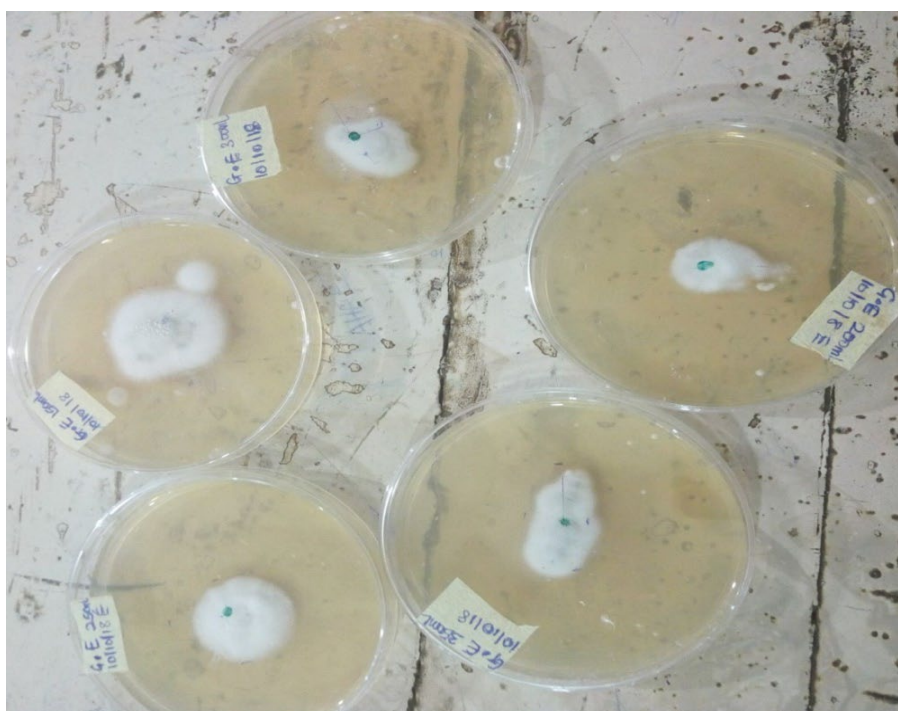


Figure 2. Antifungal potential of *Zingiber officinale* aqueous extracts against *Fusarium* sp. at different concentrations. PDA plates were centrally inoculated with a 5-mm mycelial disc of *Fusarium* sp. and treated with different concentrations (e.g., 2000 and 3000  $\mu\text{g}/\text{mL}$ ) of *Zingiber officinale* aqueous extract. Reduced colony diameter and restricted radial growth at higher concentrations indicate a dose-dependent inhibitory effect of the extract.

Table 3. Effect of various biocontrol agents on radial mycelia growth and % inhibition against *Fusarium* sp. within 120 hours of inoculation (Day 5)

Biocontrol agents	Radial mycelia growth	Percentage inhibition of mycelial growth in % $\pm$ SEP
<i>Cladosporium</i> sp. 1	2.58 $\pm$ 0.00 <sup>d,e</sup>	56.3 $\pm$ 0.32 <sup>c</sup>
<i>Gliocladium</i> sp. 1	2.71 $\pm$ 0.12 <sup>f</sup>	54.1 $\pm$ 0.69 <sup>a,b</sup>
<i>Acremonium</i> sp. 1	2.80 $\pm$ 0.33 <sup>f</sup>	52.6 $\pm$ 2.19 <sup>a</sup>
<i>Acremonium</i> sp. 2	2.64 $\pm$ 0.14 <sup>e</sup>	55.3 $\pm$ 2.58 <sup>c</sup>
<i>Trichoderma</i> sp. 1	1.67 $\pm$ 0.10 <sup>a</sup>	71.7 $\pm$ 0.15 <sup>f</sup>
<i>Trichoderma</i> sp. 2	1.90 $\pm$ 0.05 <sup>b</sup>	67.8 $\pm$ 0.03 <sup>e</sup>
<i>Aspergillus</i> sp. 1	2.40 $\pm$ 0.16 <sup>c</sup>	59.4 $\pm$ 2.37 <sup>d</sup>
<i>Aspergillus</i> sp. 2	2.56 $\pm$ 0.14 <sup>d</sup>	56.7 $\pm$ 0.76 <sup>c</sup>
<i>Penicillium</i> sp. 1	2.75 $\pm$ 0.02 <sup>f,g</sup>	53.5 $\pm$ 0.26 <sup>a</sup>
<i>Pseudomonas</i> sp. 1	2.82 $\pm$ 0.11 <sup>g</sup>	52.3 $\pm$ 0.27 <sup>a</sup>
<i>Bacillus</i> sp. 1	2.74 $\pm$ 0.02 <sup>f,g</sup>	53.6 $\pm$ 1.06 <sup>a</sup>
Control	5.82 $\pm$ 0.17 <sup>h</sup>	0.00 $\pm$ 0.00 <sup>g</sup>

Mean values with different superscript letters in a column are significantly different using DMRT at ( $p \leq 0.05$ ); SEM, standard error of the mean; SEP, standard error of the percentage.

### 3.7. Field and Storage Trials

Field applications of *Zingiber officinale* extracts (Table 4) and selected rhizospheric microorganisms (Table 5) resulted in a noticeable reduction in dry rot incidence. Treated plots showed improved plant vigor and yield compared to untreated controls. During storage, treated tubers exhibited a lower rate of rot development, indicating the potential of these

treatments in prolonging shelf life and maintaining tuber quality.

In summary, the integration of *Zingiber officinale* extracts and antagonistic rhizospheric microorganisms offers a promising strategy for managing *Fusarium*-induced dry rot in sweet potatoes. This approach not only reduces reliance on chemical fungicides but also promotes sustainable agricultural practices.

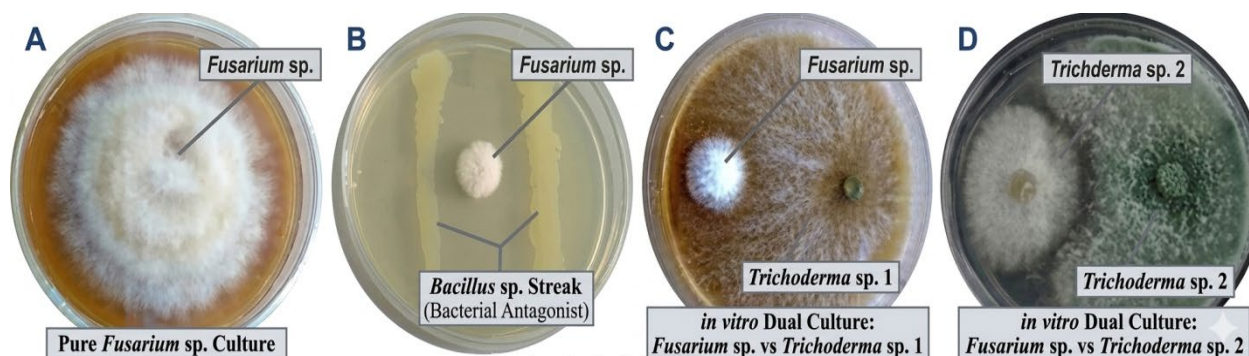


Figure 3. *In vitro* antagonistic potential of rhizospheric microorganisms against *Fusarium* sp. (A) Pure culture of *Fusarium* sp. showing typical dense, white-to-cream cottony mycelial growth on Potato Dextrose Agar (PDA). (B) Dual culture plate showing the inhibitory effect of a *Bacillus* sp. streak. The clear zone of inhibition between the bacterial streak and the fungal colony suggests the production of diffusible antifungal metabolites (antibiosis). (C) Dual culture interaction between *Fusarium* sp. and *Trichoderma* sp. 1. Note the restricted growth of the pathogen as the antagonist occupies the available niche. (D) Dual culture interaction between *Fusarium* sp. and *Trichoderma* sp. 2, demonstrating mycoparasitism and competition for space, characterized by the green conidiation of *Trichoderma* overgrowing the pathogen's mycelia.

Table 4. Antifungal efficacy of ethanol extracts of *Zingiber officinale* against *Fusarium* sp. at Day 1: 3 days after inoculation; Day 2: 6 days after inoculation; Day 3: 9 days after inoculation; and Day 4: 12days after inoculation, at week 6 and 7

Extract	LOS	NOL	LS	LOS	NOL	LS	LOS	NOL	LS	LOS	NOL	LS
	(cm)	Day 1		(cm)	Day 2		Day 3		(cm)	Day 4		
12%	71.0± 0.01 <sup>a</sup>	15.66± 0.02 <sup>abc</sup>	6.00± 0.01 <sup>a</sup>	83.66± 0.02 <sup>c</sup>	17.33± 0.01 <sup>b</sup>	4.00± 0.02 <sup>a</sup>	89.00± 0.03 <sup>ab</sup>	20.00± 0.01 <sup>b</sup>	2.33± 0.01 <sup>b</sup>	90.33± 0.02 <sup>a</sup>	22.00± 0.02 <sup>b</sup>	1.33± 0.01 <sup>abc</sup>
15%	75.00± 0.02 <sup>b</sup>	17.33± 0.01 <sup>ab</sup>	4.33± 0.02 <sup>b</sup>	85.66± 0.01 <sup>c</sup>	18.66± 0.02 <sup>b</sup>	3.66± 0.01 <sup>a</sup>	91.00± 0.01 <sup>ab</sup>	22.00± 0.02 <sup>b</sup>	1.33± 0.01 <sup>b</sup>	93.33± 0.03 <sup>a</sup>	24.66± 0.01 <sup>b</sup>	0.13± 0.00 <sup>abc</sup>
20%	80.60± 0.00 <sup>c</sup>	19.33± 0.02 <sup>c</sup>	4.33± 0.01 <sup>b</sup>	87.66± 0.02 <sup>c</sup>	20.33± 0.01 <sup>b</sup>	2.00± 0.02 <sup>a</sup>	93.00± 0.03 <sup>ab</sup>	24.66± 0.01 <sup>b</sup>	0.00± 0.00 <sup>b</sup>	95.00± 0.03 <sup>a</sup>	27.00± 0.01 <sup>b</sup>	0.00± 0.00 <sup>abc</sup>
Ctrl1	46.33± 0.01 <sup>d</sup>	8.66± 0.01 <sup>d</sup>	12.66± 0.02 <sup>c</sup>	43.33± 0.01 <sup>a</sup>	8.66± 0.02 <sup>a</sup>	16.33± 0.01 <sup>b</sup>	37.00± 0.00 <sup>a</sup>	12.66± 0.02 <sup>ab</sup>	17.66± 0.02 <sup>bc</sup>	36.00± 0.00 <sup>b</sup>	5.00± 0.01 <sup>a</sup>	18.66± 0.03 <sup>bc</sup>
Ctrl2	66.00± 0.03 <sup>e</sup>	10.00± 0.01 <sup>e</sup>	8.66± 0.00 <sup>d</sup>	70.66± 0.02 <sup>b</sup>	10.66± 0.01 <sup>a</sup>	7.00± 0.01 <sup>c</sup>	78.00± 0.02 <sup>b</sup>	13.66± 0.02 <sup>ab</sup>	6.00± 0.01 <sup>ab</sup>	83.00± 0.02 <sup>c</sup>	14.33± 0.01 <sup>c</sup>	6.33± 0.01 <sup>c</sup>
Ctrl3	84.66± 0.00 <sup>f</sup>	18.66± 0.03 <sup>bc</sup>	0.00± 0.00 <sup>e</sup>	90.33± 0.01 <sup>bc</sup>	21.00± 0.02 <sup>b</sup>	0.00± 0.00 <sup>d</sup>	94.33± 0.03 <sup>ab</sup>	23.66± 0.01 <sup>b</sup>	0.00± 0.00 <sup>b</sup>	96.33± 0.03 <sup>a</sup>	29.66± 0.01 <sup>d</sup>	0.00± 0.00 <sup>abc</sup>

Ctrl, Control; Ctrl1, Inoculated plant; Ctrl2, Ethanol; Ctrl3, Non-inoculated plant; LOS, Length of stem; NOL, Number of leaf; LS, Leaf spot. Mean values in the same column and with the same superscripts are not significantly different from one another using DMRT at (P<0.05).

Table 5. Effect of various antagonists on the growth of sweet potato plant within 48 hours-144 hours of inoculation.

Antagonists	LOS	NOL Day 1	LS	LOS	NOL Day 2	LS	LOS	NOL Day 3	LS
<i>Cladosporium</i> sp. 1	65.7± 0.57 <sup>ab</sup>	14.66± 0.02 <sup>a</sup>	5.45 ± 0.12 <sup>a</sup>	68.7± 0.39 <sup>a</sup>	16.7± 0.39 <sup>a</sup>	4.58± 0.00 <sup>b</sup>	75.5± 0.29 <sup>a</sup>	20.00± 0.01 <sup>b</sup>	2.01± 0.57 <sup>a</sup>
<i>Gliocladium</i> sp. 1	63.7± 0.77 <sup>ab</sup>	12.33± 0.01 <sup>a</sup>	5.60± 0.22 <sup>a</sup>	67.5± 0.79 <sup>a</sup>	14.5± 0.79 <sup>b</sup>	4.71± 0.12 <sup>b</sup>	70.9± 0.66 <sup>b</sup>	19.00± 0.02 <sup>b</sup>	1.02± 0.77 <sup>b</sup>
<i>Acremonium</i> sp. 1	62.4 ± 3.12 <sup>ab</sup>	12.33± 0.02 <sup>a</sup>	5.65 ± 0.23 <sup>a</sup>	65.6± 3.69 <sup>a</sup>	14.6± 3.69 <sup>b</sup>	3.80± 0.33 <sup>b</sup>	68.8± 1.59 <sup>b</sup>	16.66± 0.01 <sup>b</sup>	1.02 ± 0.12 <sup>b</sup>
<i>Acremonium</i> sp. 2	64.5 ± 1.88 <sup>ab</sup>	14.00± 0.01 <sup>a</sup>	6.55 ± 0.02 <sup>a</sup>	66.5± 2.58 <sup>a</sup>	15.5± 2.58 <sup>b</sup>	4.64± 0.14 <sup>b</sup>	69.6± 1.57 <sup>b</sup>	17.66± 0.02 <sup>ab</sup>	1.02± 1.88 <sup>b</sup>
<i>Trichoderma</i> sp. 1	80.4± 0.12 <sup>c</sup>	17.00± 0.01 <sup>ab</sup>	4.20± 0.17 <sup>a</sup>	83.0± 0.05 <sup>b</sup>	20.0± 0.05 <sup>c</sup>	2.67± 0.10 <sup>a</sup>	88.8± 0.15 <sup>c</sup>	23.66± 0.02 <sup>a</sup>	1.00± 0.00 <sup>b</sup>
<i>Trichoderma</i> sp. 2	76.9 ± 0.13 <sup>d</sup>	16.00± 0.01 <sup>ab</sup>	4.50± 0.15 <sup>a</sup>	79.6± 0.05 <sup>c</sup>	18.6± 0.05 <sup>c</sup>	2.90± 0.05 <sup>a</sup>	86.8± 0.05 <sup>c</sup>	20.5 ± 0.05 <sup>f</sup>	1.00 ± 0.00 <sup>b</sup>
<i>Aspergillus</i> sp. 1	68.7± 2.15 <sup>e</sup>	15.00± 0.01 <sup>a</sup>	5.10± 0.17 <sup>a</sup>	71.6± 3.27 <sup>d</sup>	17.6± 3.27 <sup>c</sup>	2.40± 0.16 <sup>a</sup>	75.8± 2.57 <sup>a</sup>	20.4± 0.27 <sup>d</sup>	1.07± 0.15 <sup>b</sup>
<i>Aspergillus</i> sp. 2	65.7 ± 0.83 <sup>ab</sup>	15.00± 0.01 <sup>a</sup>	6.30± 0.13 <sup>a</sup>	70.6 ± 0.76 <sup>d</sup>	18.6± 0.76 <sup>c</sup>	2.56± 0.14 <sup>a</sup>	72.20± 0.81 <sup>b</sup>	21.0 ± 0.76 <sup>cd</sup>	1.02 ± 0.13 <sup>b</sup>
<i>Penicillium</i> sp. 1	62.8± 0.29 <sup>ab</sup>	12.00± 0.01 <sup>a</sup>	6.65± 0.22 <sup>a</sup>	66.7± 0.37 <sup>a</sup>	13.7± 0.37 <sup>b</sup>	2.75± 0.02 <sup>a</sup>	70.81± 0.56 <sup>b</sup>	15.7± 0.37 <sup>ab</sup>	1.08± 0.29 <sup>b</sup>
<i>Pseudomonas</i> sp. 1	62.3± 0.37 <sup>ab</sup>	13.00± 0.01 <sup>a</sup>	5.67± 0.21 <sup>a</sup>	65.4± 0.26 <sup>a</sup>	14.4± 0.26 <sup>a</sup>	2.82± 0.11 <sup>a</sup>	68.4± 0.33 <sup>b</sup>	17.2± 0.26 <sup>a</sup>	1.03± 0.37 <sup>b</sup>
<i>Bacillus</i> sp. 1	63.7± 0.66 <sup>ab</sup>	12.00± 0.01 <sup>a</sup>	5.65± 0.21 <sup>a</sup>	67.6± 0.56 <sup>a</sup>	14.6± 0.56 <sup>a</sup>	2.74± 0.02 <sup>a</sup>	70.8± 0.66 <sup>b</sup>	16.4± 0.56 <sup>ab</sup>	1.05± 0.66 <sup>b</sup>
PCtrl	43.33± 0.02 <sup>e</sup>	8.66± 0.01 <sup>bc</sup>	16.33± 0.01 <sup>b</sup>	38.00± 0.00 <sup>e</sup>	6.66± 0.02 <sup>d</sup>	17.66± 0.02 <sup>c</sup>	36.00± 0.00 <sup>c</sup>	5.00± 0.01 <sup>a</sup>	17.66± 0.01 <sup>d</sup>
NCtrl	85.67± 0.67 <sup>f</sup>	20.0± 0.05 <sup>c</sup>	0.00± 0.00 <sup>c</sup>	90.02± 1.52 <sup>f</sup>	23.05± 0.24 <sup>e</sup>	0.00± 0.00 <sup>d</sup>	94.16± 0.13 <sup>d</sup>	25.00± 0.05 <sup>b</sup>	0.00± 0.00 <sup>e</sup>

Ctrl, Control; PCtrl, Pegative control; NCtrl, Negative control; LOS, Length of stem; NOL, Number of leaf; LS, Leaf spot. Mean values with different superscript letters in the same column are significantly different using DMRT at ( $p \leq 0.05$ ).

#### 4. Discussion

This study identified *Fusarium* sp. as the predominant and most aggressive pathogen associated with sweet potato (*Ipomoea batatas*) tuber rot in selected Nigerian farmlands. The simultaneous occurrence of *Aspergillus* sp. and additional *Fusarium* spp. suggests a complex disease environment that may influence infection dynamics and management outcomes. Noticeable morphological variability among *Fusarium* isolates corresponded with differences in virulence, as some *Fusarium* strains induced severe rot symptoms within five days, highlighting the pathogen's destructive capacity. Phytochemical analysis revealed the presence of antimicrobial compounds such as saponins, alkaloids, phenols, and glycosides in the tested botanicals, with *Zingiber officinale* (ginger) exhibiting particularly strong antifungal activity. Furthermore, antagonism assays demonstrated effective suppression of *Fusarium* sp., especially by *Trichoderma* sp.,

underscoring the potential of botanical extracts and biocontrol agents in sustainable disease management.

The high prevalence of *Fusarium* sp. (61.2%) found in this study confirms it as the dominant driver of sweet potato dry rot in the study area. These findings align with global trends where *Fusarium* species exhibit high phenotypic plasticity and virulence [16-18]. The rapid disease progression observed in the pathogenicity assays underscores the significant economic threat posed by *Fusarium* sp. to sweet potato cultivation, as previously reported [17]. The notable antifungal activity of *Zingiber officinale* observed in this study may be attributed to its high content of phenolic compounds and essential oils, which possess well-established antimicrobial properties [19]. The superior inhibitory effect of *Z. officinale* against *Fusarium* sp. is consistent with earlier findings showing that an extract concentration of 3 g/20 mL completely suppressed fungal growth [20]. Additionally, previous studies have confirmed that *Z.*

*officinale* contains bioactive phenolics and volatile oils capable of inhibiting the growth of various microorganisms [21]. Thus, the exceptional antifungal activity of *Zingiber officinale* can be attributed to its dense concentration of alkaloids (0.7305 g/mL) and saponins (0.8165 g/mL), which likely disrupt fungal cell membrane integrity [22].

This study clearly demonstrates the potential of biocontrol agents in managing *Fusarium* sp. infections in sweet potato cultivation. Among the tested antagonists, *Trichoderma* sp. 1 consistently exhibited the highest inhibition of *Fusarium* sp. mycelial growth *in vitro*, indicating its superior antagonistic capacity under the experimental conditions. The pronounced inhibitory effect observed in this study corroborates earlier reports highlighting the efficacy of *Trichoderma* species against *Fusarium*-associated diseases. Fatima et al. [23] documented that strains of *Trichoderma* sp. were sufficiently potent to suppress or prevent disease development caused by several plant pathogens. Similarly, Pastrana et al. [24] demonstrated that *Trichoderma* spp. significantly reduced crown and root rot of strawberry caused by *Fusarium* sp. In the present study, we observed variation in inhibitory activity among our *Trichoderma* isolates, with one isolate showing greater percentage inhibition than another. Such variability in antagonistic potential among different *Trichoderma* isolates is well documented [25]. Numerous studies have confirmed the effectiveness of various *Trichoderma* species in inhibiting rot fungi, including *Fusarium* species [26–27]. The strong suppression observed in this work may be attributed to well-documented mechanisms of *Trichoderma* spp., such as rapid competition for nutrients and space, mycoparasitism, and the production of antifungal metabolites [27]. Collectively, these findings reinforce the suitability of the most potent *Trichoderma* isolate (*Trichoderma* sp. 1) obtained in this study as a promising component of integrated disease management strategies for controlling *Fusarium* sp. in sweet potato cultivation.

Despite the significant findings of this study, certain limitations must be acknowledged. Primarily, while the identification of *Fusarium* sp. and rhizospheric antagonists was conducted using rigorous morphological and biochemical keys, molecular characterisation, such as *tef1-α* or ITS region sequencing, was not performed. Although morphological markers remain a foundational diagnostic tool in mycology [16], future research should incorporate sequence-based identification to confirm genetic diversity among isolates. Additionally, while the integrated management approach showed high efficacy in Ogun State, multi-location trials across diverse agro-ecological zones would further validate the scalability of these botanical and biological interventions. Future research should also focus on field trials to evaluate the practical applicability of these control measures and explore the synergistic effects of combining botanical and biological approaches for sustainable disease management.

In conclusion, this study demonstrates that an integrated strategy using *Zingiber officinale* extract and *Trichoderma* spp. provides a potent, eco-friendly alternative to synthetic fungicides for managing sweet potato dry rot. The high alkaloid and phenolic content of ginger, combined with the mycoparasitic nature of rhizospheric antagonists, significantly reduces disease incidence and promotes plant vigour. These findings offer a sustainable framework for smallholder farmers to protect their yields and improve food security.

### Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

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