



Research Article

Pathogenicity and Control of Foliar Endophytic Fungi of *Citrus sinensis* L. (Sweet Orange) Using Plant Extracts

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ABSTRACT

Endophytic colonisation of plant tissues by microbes is an important determinant of plant health and productivity. A study was carried out to evaluate the pathogenicity and control of endophytic fungi isolated from citrus leaves in Lafia. Endophytic fungi recovered from citrus leaves were morphologically identified and subjected to pathogenicity tests. Pathogenic endophytes selected from the pathogenicity test were administered with different concentrations of aqueous and ethanolic extracts of *Carica papaya* and *Azadirachta indica*. Results revealed that the endophytic fungi belonged to three species: *Colletotrichum asianum*, *Colletotrichum nymphaeae*, *Talaromyces* sp., *Talaromyces funiculosus*, and *Bipolaris* sp. Of the identified endophytic fungi, *C. asianum* was the most prevalent (61.82%), followed by *C. nymphaeae* (32.73%), while *T. funiculosus*, *Talaromyces* sp., and *Bipolaris* sp. all had 1.82% occurrence within the studied area. Pathogenicity tests showed that *C. asianum* was the most pathogenic (13.30%), followed by *C. nymphaeae* (6.67%) ($P \geq 0.05$). Tests of fungicidal activity of *Carica papaya* and *Azadirachta indica* leaf extracts against the pathogens showed that aqueous extracts of *Carica papaya* were most potent against the test organisms, inhibiting at least 93.92% of the test organisms at all tested concentrations. Differences in growth inhibition of the pathogens by the extracts were significant ($P < 0.05$). The study revealed that *Colletotrichum asianum* and *C. nymphaeae* are the primary pathogenic endophytes of citrus leaves in Lafia, while aqueous leaf extracts of *Carica papaya* possess exceptional antifungal activity against these pathogens, offering promising potential as an eco-friendly bio-fungicide for citrus disease management.

Keywords: Biocontrol; Biofungicidal activity; *Citrus sinensis*; Endophytic fungi; Pathogenicity

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INTRODUCTION

Endophytic fungi are microorganisms that reside within plant tissues without causing visible symptoms of disease (Wilson, 1995). These fungi belong to different taxonomic groups, including Ascomycota, Basidiomycota, and Zygomycota (Rodriguez *et al.*, 2009). The diversity of endophytic fungi is influenced by factors such as plant species, geographical location, and environmental conditions (Arnold & Lutzoni, 2007). Endophytic fungi have been identified

in a wide range of plant species and are known to promote plant growth, enhance stress tolerance, and produce bioactive compounds with potential applications in agriculture and medicine (Adeleke *et al.*, 2021).

These microorganisms are now recognized as vital components of plant microbiomes, contributing to various aspects of plant biology, including growth promotion, disease resistance, and stress tolerance (Arnold & Lutzoni, 2007; Hardoim *et al.*, 2015). The

leaves of *Citrus sinensis* plants, particularly those of *Citrus sinensis* (sweet orange), present a unique microhabitat for such fungi, owing to their complex secondary metabolites and biochemical interactions with their endophytes (Goudeau *et al.*, 2008).

The diversity of endophytic fungi associated with *Citrus sinensis* has gained attention due to their potential applications in agriculture and medicine. Studies have reported that endophytes can produce bioactive compounds, such as alkaloids, terpenoids, and phenolics, which may possess antimicrobial, antifungal, and phytotoxic properties (Vishwakarma *et al.*, 2025). This biotechnological potential accentuates the importance of exploring endophytic fungal communities in economically important crops like orange.

Despite the popularity, and large-scale cultivation of citrus in Nigeria, there is a dearth of knowledge on the diversity, pathogenicity and biological control potentials of endophytic fungi of citrus in Lafia, Nasarawa State, Nigeria. Furthermore, the challenge of the high cost of chemical fungicides and their associated environmental and health risks call for the adoption of more sustainable and environmentally friendly approaches in the management of fungal pathogens of crop plants. Therefore, this study was aimed at evaluating the pathogenicity and control of endophytic fungi from citrus leaves in Lafia, Nigeria.

MATERIALS AND METHODS

Description of the Study Site

The study was conducted in Lafia, Nasarawa State, Nigeria. Lafia is the capital of Nasarawa state, located on Latitude 8°29'17.99"N, and longitude 8°30'59.99"E, in the Southern Guinea Savannah Region of North-central Nigeria.

Collection of Samples

Orange leaves were collected from apparently healthy and disease-free orange trees from farmlands within the four cardinal locations of Lafia, namely Lafia East, Lafia North, Lafia South, and Lafia West. The disease-free leaves of *Citrus sinensis* L. were collected from four farmlands which were randomly selected from the four cardinal locations. From each farm, four healthy orange leaves were collected and conveyed in sterile polyethylene bags to the Plant Science and Biotechnology Laboratory, Federal University of Lafia, Nasarawa State, for further processing.

Surface Sterilization of *Citrus sinensis* Leaves

The orange leaf tissues were aseptically cut to sizes of about 2 cm² with the aid of scalpel and surface-sterilized by sub-merging in 1% sodium hypochlorite

solution for two minutes, followed by 70% ethanol for two minutes. Thereafter, the surface disinfected plant tissues were rinsed three times in sterile distilled water for 1 minute each time, and blotted dry on sterilized Whatman No.1 filter paper to remove excess water. After surface sterilization, the imprint technique was used to confirm the efficacy of surface sterilization before the sterilized tissues were plated onto Potato Dextrose Agar (PDA) supplemented with 0.5% streptomycin, to inhibit bacterial growth. Two tissues each were plated from each sampled leaf, at the rate of two tissues per plate, and spaced about 5cm apart. The plates were incubated at room temperature for 3-5 days until fungal colonies emerged. Pure cultures of fungal isolates were obtained by transferring single hyphal tips to fresh PDA plates.

Identification of Fungal Isolates

The pure cultures of isolated endophytic fungi were subjected to morphological characterisation. Colony characteristics, such as growth rate, colour and textures were recorded, as well as microscopic features, such as shape and pigmentation of conidia, structure of hyphae, and conidiophore (Barnett and Barry, 1998). The isolated fungi were identified with the aid of appropriate identification guides (Goudeau *et al.*, 2008).

Pathogenicity Test

The leaf bioassay method of Terna *et al.* (2025) was used for pathogenicity tests. The tests were conducted to determine the virulence of the endophytic fungal species on healthy *Citrus sinensis* leaves. Healthy citrus leaves were rinsed with water and surface sterilized by swabbing with 70% ethanol. The disinfected leaves were further wounded slightly with a sterilized needle, and artificially inoculated with 7 mm diameter mycelial plugs of endophytic fungi obtained from five days old cultures. Leaves in the control experiments were inoculated with sterile PDA plugs in place of fungal mycelia. Inoculated leaves were placed in sterile plastic containers and incubated for a period of five to seven days. Inoculated leaves were kept hydrated by attaching moist sterile cotton balls on their petioles. Disease symptoms were evaluated visually by estimating the percentage of diseased tissue in relation to the entire leaf area as reported by Bock *et al.* (2010).

Preparation of Plant Extracts

The revised procedure of Handa *et al.* (2008) was used for the preparation of plant extracts. The leaves of *Carica papaya* and *Azadirachta indica* were washed and dried under room temperature for 12 days. The dried leaves were ground to powder using a mortar

and pestle, and placed in sterilized glass jars. Ethanolic extracts were obtained by soaking 50 g of the powdered plant materials in 500 mL of 40% ethanol, while aqueous extracts were obtained by soaking 50 g of the powdered plant materials in 500 mL of sterile distilled water for 24 hours at room temperature. The extracts were filtered using a muslin cloth, and the filtrates were stored in sterilised glass jars until required.

Biofungicidal Activity of Plant Extracts

Different concentrations of the extracts, namely 0%, 25%, 50%, 75% and 100% were used for the determination of the bio-fungicidal effects of the plant extracts on the pathogenic endophytic fungi, using the pour plate technique. Aqueous and ethanolic leaf extracts were mixed with PDA and allowed to solidify. Thereafter, 7 mm diameter mycelial discs of the pathogens were inoculated at the centre of the Agar-extract mix. Radial growth diameters of the pathogens were recorded after six days, and used for the calculation of percentage radial growth inhibition using the formula below:

$$PRGI = \frac{DPC - DPE}{DPE} \times 100$$

Where PGRI = Percentage of Radial Growth Inhibition

DPC = Diameter of pathogen in control

DPE = Diameter of pathogen administered with plant extracts

Experimental Design and Data Analysis

The experiment was set up using the Completely Randomized Design (CRD) with three replicates. Data obtained from the study was subjected to Analysis of Variance (ANOVA) at 5% level of probability using the Minitab Software, Version 20. Means were separated using the Fisher's Least Significant Difference (LSD).

RESULTS

Results of morphological identification of endophytic fungi recovered from *Citrus sinensis* leaves in Lafia are presented in Table 1 and Plates 1 - 5. On the basis of morphological characteristics such as colony colour, texture, elevation, growth rate, margins, pigmentation, diameter, hyphal structure, type and structure of conidiophore, in addition to shape and texture of conidia, the endophytic isolates were identified as *Colletotrichum asianum* (34 isolates), *Colletotrichum nymphaeae* (18 isolates), *Talaromyces* sp. (1 isolate), *Talaromyces funiculosus* (1 isolate), and *Bipolaris* sp. (1 isolate). A total of 55 isolates of endophytic fungi were recovered from the citrus leaves.

Table 2 presents the occurrence of the different endophytic fungi on citrus leaves in the four studied

locations in Lafia. Of the isolated fungi, *C. asianum* was the most occurring (61.82%), followed by *C. nymphaeae* (32.73%), *Talaromyces* sp. (1.82%), *T. funiculosus* (1.82%), and *Bipolaris* sp. (1.82%). Of the studied locations, Lafia West had the highest number of fungal species (n=4), while the other three locations had two species each. The fungal species identified in citrus leaves from Lafia North were *C. nymphaeae* and *C. asianum*, while *C. asianum* and *Talaromyces* sp. were identified from Lafia South, *C. nymphaeae* and *C. asianum* from Lafia East, and *C. nymphaeae*, *C. asianum*, *T. funiculosus*, and *Bipolaris* sp. were isolated from citrus leaves from Lafia West. Results of pathogenicity tests of the endophytic fungi recovered from citrus leaves are presented in Table 3 and Plate 6. The highest tissue damage of citrus leaves (13.00%) was caused by *C. asianum* isolate from Lafia South, followed by *C. nymphaeae* from Lafia North (6.67%), and *C. nymphaeae* from Lafia West (3.33%). Citrus leaves inoculated with endophytic *Bipolaris* sp., *Talaromyces* sp., and *T. funiculosus* showed no symptoms of disease. Differences in tissue damage by the different endophytic fungi on the inoculated leaves were not significant ($P \geq 0.05$).

Table 4 presents the antifungal activity of ethanolic and aqueous leaf extracts of *Carica papaya* against endophytic *C. nymphaeae* and *C. asianum* causing leaf necrosis of citrus in Lafia. Administration of 100%, 75% and 50% of aqueous extracts of *Carica papaya* yielded the highest percentage of radial growth inhibition (RGI) of *C. nymphaeae* (100.00%), followed by 25% (93.92% RGI), 25% ethanolic extract (50.00% RGI), and 75% ethanolic extract (0.52% RGI). Growth of *C. nymphaeae* was not inhibited after administration of 50% and 100% of ethanolic leaf extracts. Differences in the radial growth inhibition of *C. nymphaeae* by the different leaf extracts of *Carica papaya* were significant ($P < 0.05$).

Similar to *C. nymphaeae*, the highest growth inhibition of *C. asianum* (100.00%) was yielded by all aqueous concentrations (i.e. 100%, 75%, 50%, and 25%) of *Carica papaya* leaf extracts, followed by 50% ethanolic extract (50.00% RGI), 100% ethanolic extract (45.97% RGI), 50% ethanolic extract (40.30% RGI), and 75% ethanolic extract (20.97% RGI). Differences in the radial growth inhibition of *C. asianum* by the different extracts of *Carica papaya* were significant ($P < 0.05$).

Table 1: Morphological characteristics of endophytic fungi recovered from *Citrus sinensis* leaves in Lafia

Group	Macromorphology				Micromorphology			ID
	CC	TEM	Pigmentation	MCD (cm)	Hyphae	Conidiophore	Conidia	
1.	Orange to yellow	Colonies were flat, circular, a bit slimy, with a powdery texture, and entire margins	Orange	6.18	Septate with long branching pattern	Conidiophores were modified hyphal branches, rough and septate	Cylindrical and smooth-walled	<i>Colletotrichum asianum</i> (34 isolates)
2.	Orange mixed with gray	Colonies were slightly raised, circular, with entire margins	Orange mixed with gray	5.90	Extensively branched and septate	Conidiophores were modified hyphal branches, rough and septate	Cylindrical and smooth-walled	<i>Colletotrichum nymphaeae</i> (18 isolates)
3.	Gray	Raised, wooly irregular, with filiform margins	Gray mixed with brown	8.10	Septate, with constricted and scantily branched hyphae	Phialides were slender, elongated, and tapered	Oval and smooth-walled	<i>Talaromyces</i> sp. (1 isolate)
4.	Biege to grayish brown	Colonies were flat, velvety, irregular, with filiform margins	Blackish brown	8.10	Septate, and scantily branched	Phialides were slender, enlongated, cylindrical but not tapered.	Tick walled, and ranged in shape from oval to sub-oval	<i>Talaromyces funiculosus</i> (1 isolate)
5.	Grayish green	Colonies were umbonate, wooly, circular, slow-growing, with filiform margins	Blackish brown	2.93	Highly septate, branched, and constricted	Conidiophores were modified hyphal branches, rough and septate	Elongated, cylindrical, slender, tapered, and segmented	<i>Bipolaris</i> sp. (1 isolate)

Key: CC = Colony Colour; TEM = Texture, Elevation, and Margins; MCD = Mean Colony Diameter on PDA after 5 Days

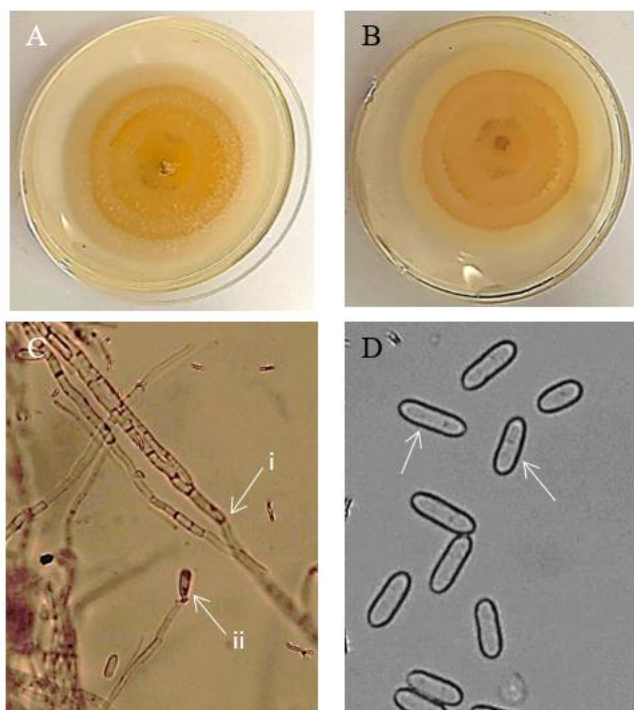


Plate 1: Morphological characteristics of endophytic *C. asianum* isolated from citrus leaves

A) Colony appearance after 5 days on PDA; B) Colony pigmentation; Ci) Septate hyphae; Cii) Attached conidium; D) Mature detached cylindrical conidia (x40)

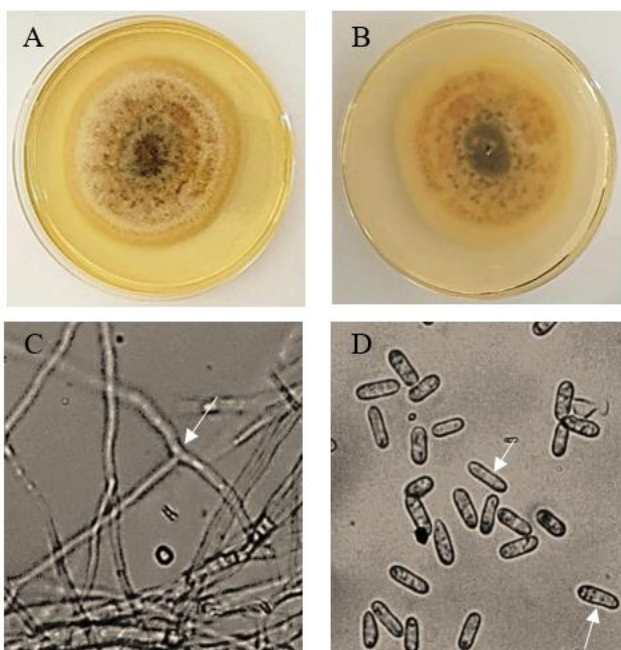


Plate 2: Morphological characteristics of endophytic *C. nymphaeae* isolated from citrus leaves

A) Colony appearance after 5 days on PDA; B) Colony pigmentation; C) Hyphal branching; D) Cylindrical conidia (x40).

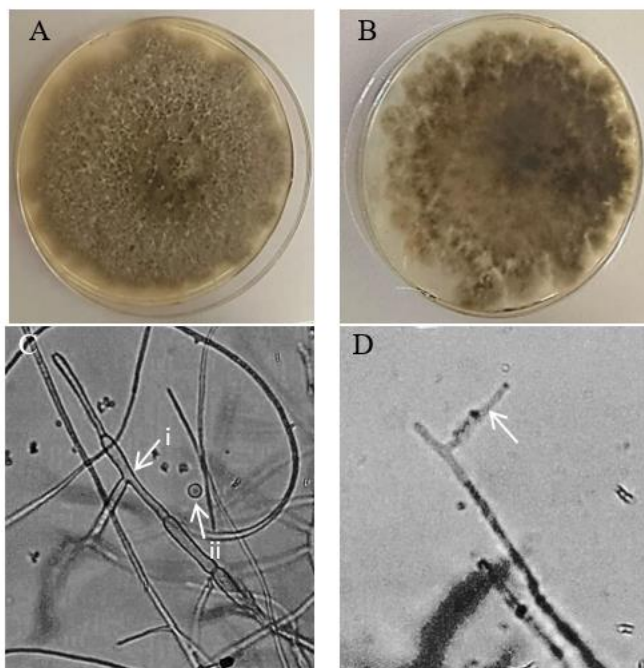


Plate 3: Morphological characteristics of endophytic *Talaromyces* sp. isolated from citrus leaves

A) Colony appearance after 5 days on PDA; B) Colony pigmentation; Ci) Hyphal branching; Cii) Globose conidium; D) Slender elongated phialide (×40).

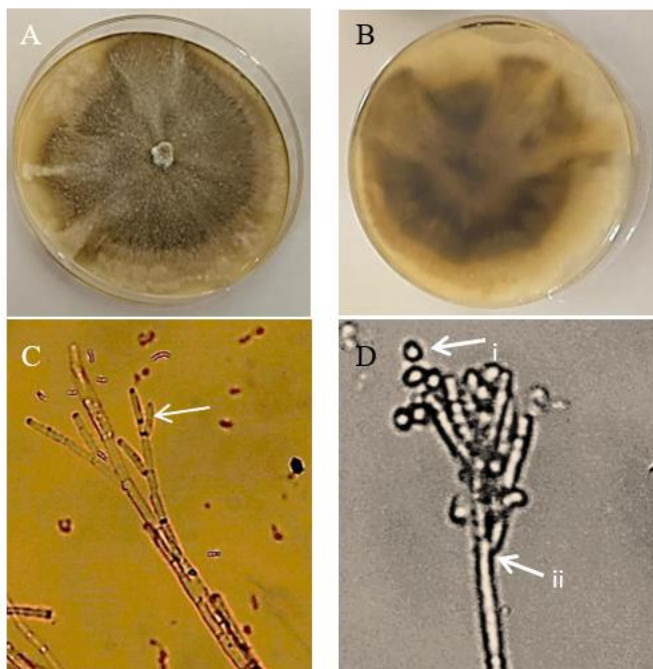


Plate 4: Morphological characteristics of endophytic *T. funiculosus* isolated from citrus leaves

A) Colony appearance after 5 days on PDA; B) Colony pigmentation; C) Cylindrical phialide; Di) Globose conidium; Dii) Conidiophore branching (×40).

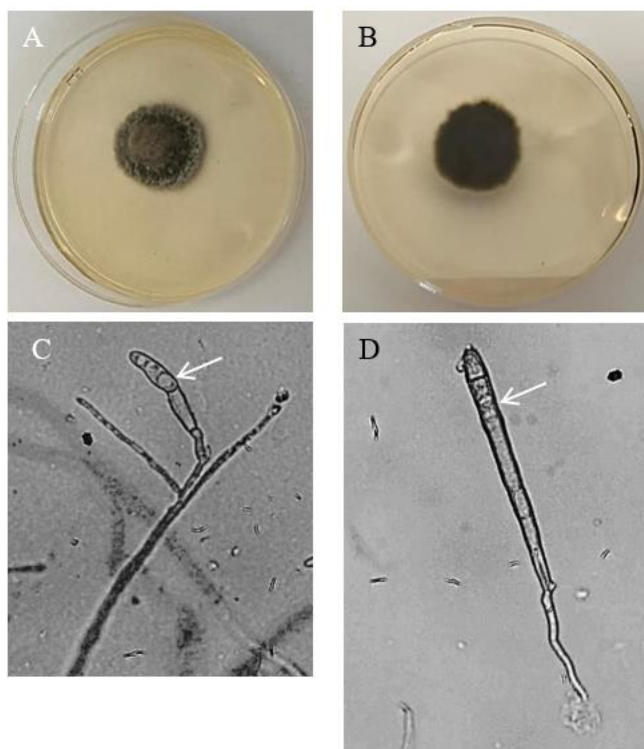


Plate 5: Morphological characteristics of endophytic *Bipolaris* sp. isolated from citrus leaves

A) Colony appearance after 5 days on PDA; B) Colony pigmentation; C) Attached conidium; D) Mature detached cylindrical and elongated conidium (x40).

Table 2: Occurrence of endophytic fungi of citrus leaves in the studied locations

Location	<i>C. nymphaeae</i>	<i>C. asianum</i>	<i>Bipolaris</i> sp.	<i>Talaromyces</i> sp.	<i>Talaromyces funiculosus</i>	Total
Lafia North	1(1.82%)	7(12.73%)	-	-	-	8(14.55%)
Lafia South	-	15(27.27%)	-	1(1.82%)	-	16(29.09%)
Lafia East	16(29.09%)	1(1.82%)	-	-	-	17(30.91%)
Lafia West	1(1.82%)	11(20.00%)	1(1.82%)	-	1(1.82%)	13(23.64%)
Total	18(32.73%)	34(61.82%)	1(1.82%)	1(1.82%)	1(1.82%)	55(100%)

Table 3: Pathogenicity of endophytic fungi recovered from citrus leaves

Isolate Code	Isolates	Source	% Tissue Damage
OS2B	<i>C. asianum</i>	Lafia South	13.30 ^a
OW4B	<i>C. asianum</i>	Lafia West	0.00 ^a
ON1B	<i>C. asianum</i>	Lafia North	0.00 ^a
ON2B	<i>C. nymphaeae</i>	Lafia North	6.67 ^a
OW2A	<i>C. nymphaeae</i>	Lafia West	3.33 ^a
OE3B	<i>C. nymphaeae</i>	Lafia East	0.00 ^a
OW3C	<i>Bipolaris</i> sp.	Lafia West	0.00 ^a
OS4B	<i>Talaromyces</i> sp.	Lafia South	0.00 ^a
OW4D	<i>T. funiculosus</i>	Lafia West	0.00 ^a
Control	-	-	0.00 ^a

Means followed by the same superscripts within the same column are not significantly different ($P \leq 0.05$)

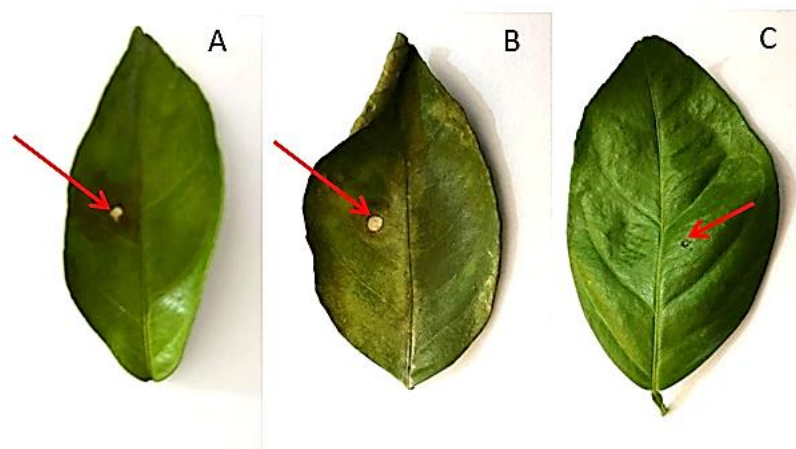


Plate 6: Pathogenicity of endophytic fungi on citrus leaves

A: *C. nymphaeae*; B: *C. asianum*; C: control. Red arrow shows point of inoculation.

Table 4: Antifungal activity of ethanolic and aqueous leaf extracts of *Carica papaya* against *C. nymphaeae* and *C. asianum*

Extract	Concentration (%)	% Radial Growth Inhibition	
		<i>C. nymphaeae</i>	<i>C. asianum</i>
Ethanolic	0	0.00 ^b	0.00 ^b
	25	50.00 ^{ab}	50.00 ^{ab}
	50	0.00 ^b	40.30 ^b
	75	0.52 ^b	20.97 ^b
	100	0.00 ^a	45.97 ^b
Aqueous	0	0.00 ^b	0.00 ^b
	25	93.92 ^a	100 ^a
	50	100.00 ^a	100 ^a
	75	100.00 ^a	100 ^a
	100	100.00 ^a	100 ^a

Means followed by the same superscripts within the same column are not significantly different ($P \leq 0.05$)

Results of the antifungal activity of ethanolic and aqueous leaf extracts of *Azadirachta indica* against *C. nymphaeae* and *C. asianum* causing leaf necrosis of citrus are presented in Table 5. The highest growth inhibition of *C. nymphaeae* (100.00%) was produced by 25% ethanolic extract of *Azadirachta indica*, followed by 25% aqueous extract (58.21% RGI), 50% aqueous extract (54.21% RGI), 100% aqueous extract (47.39% RGI), 75% aqueous concentration (46.60% RGI), 50% ethanolic extract (45.05% RGI), 100% ethanolic extract (13.31% RGI), and 75% ethanolic extract (7.12% RGI). Growth inhibitions were not observed in the control. Differences in the radial growth inhibitions of *C. nymphaeae* by the different

extracts of *Azadirachta indica* were significant ($P < 0.05$).

Similar to *C. nymphaeae*, the highest radial growth inhibition of *C. asianum* (100%) was caused by 25% concentration of ethanolic leaf extracts of *Azadirachta indica*, followed by 75% aqueous extracts (64.62%), 50% aqueous extracts (50.40% RGI), 25% aqueous extracts (44.60% RGI), 100% ethanolic extracts (43.21% RGI), 75% ethanolic extracts (30.16% RGI), and 50% ethanolic extracts (29.50% RGI). Growth inhibitions were not observed in the control. Differences in the radial growth inhibition of *C. asianum* by the different extracts of *Azadirachta indica* were significant ($P < 0.05$).

Table 5: Antifungal activity of ethanolic and aqueous leaf extracts of *Azadirachta indica* against *C. nymphaeae* and *C. asianum*

Extract	Concentration (%)	% Radial Growth Inhibition	
		<i>C. nymphaeae</i>	<i>C. asianum</i>
Ethanolic	0	0.00 ^c	0.00 ^e
	25	100.00 ^a	100 ^a
	50	45.05 ^b	29.50 ^{de}
	75	7.12 ^c	30.16 ^{cde}
	100	13.31 ^c	43.21 ^{bcd}
Aqueous	0	0.00 ^c	0.00 ^e
	25	58.21 ^b	44.60 ^{bcd}
	50	54.10 ^b	50.40 ^{bcd}
	75	46.60 ^b	64.62 ^{bc}
	100	47.39 ^b	76.92 ^{ab}

Means followed by the same superscripts within the same column are not significantly different ($P \leq 0.05$)

DISCUSSION

The macromorphological traits such as colony colour, texture, elevation, and margins present distinctive features of the identified fungi. For instance, *Colletotrichum nymphaeae* exhibited an orange and gray coloration with slightly raised, circular colonies, which is considered typical of the species (Trkulja *et al.*, 2024). The mean colony diameter of 5.90 cm – 6.18 cm for *Colletotrichum* indicates moderate growth rates typically associated with this group. Contrastingly, *Talaromyces* sp. presented a gray, raised, wooly appearance, with an impressive mean colony diameter of 8.10 cm. This suggests a more vigorous growth potential, possibly contributing to its competitive advantages in nutrient acquisition (Yilmaz *et al.*, 2014). It is interesting to note that *Talaromyces funiculosus* also displayed similar dimensions, indicating a potential niche overlap among these taxa.

Micromorphological assessment revealed detailed structural components crucial for fungal identification. Hyphal characteristics varied significantly among the fungal isolates. For example, *Colletotrichum nymphaeae* and *Colletotrichum asianum* both showed extensively branched and septate hyphae, and cylindrical conidia typical of the *Colletotrichum* genus, which is known for its pathogenicity on various plant species (Agrios, 2005). Similarly, *Bipolaris* sp. showed highly septate and branched hyphae, with conidia that were elongated and segmented. Such features are indicative of the genus's adaptability and could contribute to its survival and pathogenicity in plant systems (Manamgoda *et al.*, 2012).

The investigation into the occurrence of endophytic fungi from citrus leaves in Lafia revealed significant location-based variation in the presence of different

species. Notably, the high occurrence of *Colletotrichum asianum* may indicate its ecological adaptability or aggressive pathogenicity within citrus crops, which is supported by the identified tissue damage associated with this species during pathogenicity tests (Rodriguez *et al.*, 2009).

The non-significant pathogenicity for isolates belonging to *Bipolaris* sp. and *Talaromyces* spp., could signal their potential role as non-pathogenic endophytes, contributing to plant health by occupying niches that may otherwise be exploited by more harmful pathogens (Hardoin *et al.*, 2015). Variations across locations suggest that environmental factors, including the specific microclimate and soil characteristics, may impact the diversity and abundance of endophytic fungi in citrus microhabitats (Juybari *et al.*, 2019).

The complete inhibition (100% RGI) of *Colletotrichum asianum* and *Colletotrichum nymphaeae* by aqueous leaf preparations of *Carica papaya* could be a result of the high solubility of its polar bio-active constituents. Papaya leaves are rich in hydrophilic proteolytic enzymes (such as papain and chymopapain), glucosinolates, and polar polyphenols that readily dissolve in water. These compounds disrupt fungal cell membrane integrity and hydrolyze structural cell wall proteins (Jinhui *et al.*, 2024). Conversely, the decreased efficacy observed in higher ethanolic concentrations suggests that ethanol may induce structural denaturation or conformational changes in key antifungal proteins, thereby reducing their biocontrol activity (Jinhui *et al.*, 2024).

By exhibiting maximum biocontrol potency (100% RGI) against both *C. nymphaeae* and *C. asianum* specifically at its lowest ethanolic concentration (25%), the results for neem are in contrast of the results observed with the application of papaya leaf

extracts. This inverse concentration-dependent effect represents a classic non-linear or biphasic response often observed in botanical extract bioassays. The primary antifungal constituents in neem leaves are moderately lipophilic tetranortriterpenoids (such as azadirachtin, nimbin, and salannin) alongside bioactive polyphenols (Mahmoud *et al.*, 2011). At a lower ethanolic strength (25%), these hydrophobic compounds remain finely dispersed as a colloidal suspension within the aqueous culture medium, optimizing their surface area contact and cellular uptake across the fungal hyphae.

CONCLUSION

The study identified *C. asianum*, *C. nymphaeae*, *Talaromyces* sp., *Talaromyces funiculosus*, and *Bipolaris* sp. as the endophytic fungi present within the leaf tissues of *Citrus sinensis* in Lafia, of which *C. asianum* was the most prevalent. Test of pathogenicity of the endophytic fungi showed that *C. asianum* was the most pathogenic, followed by *C. nymphaeae*, while test of biofungicidal activity of plant extracts against the pathogenic endophytes revealed that aqueous extracts of *Carica papaya* were the most potent. The study revealed that *Colletotrichum asianum* and *C. nymphaeae* are the primary pathogenic endophytes of citrus leaves in Lafia, while aqueous leaf extracts of *Carica papaya* possess exceptional antifungal activity against these pathogens, offering a promising potential as an eco-friendly bio-fungicide for citrus disease management.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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