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Comparative Antifungal Efficacy of Cinnamon (*Cinnamomum burmannii*) and Turmeric (*Curcuma longa*) Extracts Against Postharvest Anthracnose of Papaya

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Abstract. Anthracnose is a major postharvest disease that reduces the quality and marketability of papaya fruits. This study evaluated and compared the antifungal activity of cinnamon (*Cinnamomum burmannii*) leaf extract and turmeric (*Curcuma longa*) rhizome extract against *Colletotrichum brevisporum* under *in vitro* and *in vivo* conditions. The experiment was arranged in a Completely Randomized Design (CRD) consisting of ten treatments with four replicates. Treatments included cinnamon and turmeric extracts at concentrations ranging from 0.25% to 1.00%, a propineb fungicide treatment, and an untreated control. Both extracts significantly inhibited mycelial growth, suppressed conidial germination, and reduced disease development compared with the untreated control ($p < 0.05$). Turmeric extract consistently exhibited greater antifungal activity than cinnamon extract. At a concentration of 1.00%, turmeric extract reduced colony diameter by 46.84%, decreased disease severity at 6 days after inoculation by 34.6%, and completely inhibited conidial germination compared with the untreated control. Its performance also approached that of propineb during the early stages of infection. However, this study evaluated crude extracts under controlled laboratory and postharvest conditions without phytochemical characterization or validation under commercial storage systems. These findings suggest that turmeric rhizome extract is a promising candidate for further development as an environmentally friendly component of integrated postharvest management of papaya anthracnose, although additional studies on phytochemical composition, formulation, and commercial-scale validation are required before practical application.

Keywords: anthracnose; antifungal agents; *Colletotrichum brevisporum*; postharvest disease management

1. Introduction

Papaya (*Carica papaya* L.) is an important tropical fruit crop widely cultivated in Indonesia and valued for its economic contribution (Arrijani & Setyawati, 2023). In addition to its nutritional richness in vitamins, minerals, and bioactive enzymes, papaya plays a significant role in supporting smallholder farmers and regional fruit markets. However, its climacteric ripening behavior and high moisture content make papaya highly susceptible to postharvest diseases that reduce fruit quality, marketability, and shelf life.

Among postharvest diseases, anthracnose caused by *Colletotrichum brevisporum* is one of the most destructive diseases affecting papaya during storage and distribution (Getnet et al., 2024; Tan et al., 2023). The pathogen infects fruit tissues and produces water-soaked lesions that develop into dark, sunken necrotic spots, resulting in rapid fruit deterioration under favorable environmental conditions (Saini et al., 2016). Because infection often remains latent during fruit development and becomes active during ripening, anthracnose can cause substantial postharvest losses and significantly reduce the economic value of fresh fruit.

Management of anthracnose commonly relies on synthetic fungicides. Although effective, their continuous use may result in pesticide residues, environmental contamination, and the development of fungicide-resistant pathogen populations (Goswami et al., 2018). Increasing consumer demand for safer food products and stricter regulations on pesticide residues have intensified the search for environmentally friendly alternatives for postharvest disease management.

Plant-derived extracts have attracted considerable attention as environmentally friendly alternatives to synthetic fungicides. Cinnamon contains cinnamaldehyde, eugenol, and other phenolic compounds

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capable of disrupting fungal cell membranes and inhibiting fungal growth, whereas turmeric is rich in curcuminoids and sesquiterpenes that interfere with fungal metabolism and suppress mycelial development (Cruz et al., 2024; El-Saadony et al., 2023; Kowalska et al., 2021; Sanla-Ead et al., 2012). Although cinnamon bark has been more extensively investigated because of its high cinnamaldehyde content, cinnamon leaves represent a renewable and more sustainable source of bioactive compounds. Leaves can be harvested without destroying the plant and still contain considerable amounts of antifungal constituents, making them an attractive alternative for botanical fungicide development (Kowalska et al., 2021; Darmadi et al., 2022)

Recent studies have demonstrated the antifungal activity of turmeric against *Colletotrichum* spp. (Akin et al., 2024; Alvindia et al., 2022) and cinnamon extracts against several phytopathogenic fungi (Darmadi et al., 2022; Sudirga et al., 2024). However, most previous studies evaluated these botanical extracts independently, used different pathogen species or experimental conditions, and primarily focused on a single biological response, such as inhibition of mycelial growth. Consequently, direct comparisons of the relative antifungal efficacy of cinnamon leaf and turmeric rhizome extracts remain limited. Furthermore, few studies have simultaneously assessed multiple stages of fungal development, including mycelial growth, conidial germination, disease incidence, disease severity, and ultrastructural changes within a single experimental framework. Because inhibition of fungal growth under laboratory conditions does not necessarily correspond to effective disease suppression on fruit, an integrated comparison under identical experimental conditions is scientifically necessary to provide a more comprehensive evaluation of botanical antifungal efficacy. Therefore, this study aimed to compare the antifungal efficacy of cinnamon leaf and turmeric rhizome extracts against *Colletotrichum brevisporum* under both *in vitro* and *in vivo* conditions and to evaluate their potential as environmentally friendly alternatives for the integrated postharvest management of papaya anthracnose.

2. Materials and Methods

2.1 Pathogen Isolation and Morphological Identification

Papaya fruits exhibiting typical anthracnose symptoms were collected from local production fields in Lampung Province, Indonesia. Small tissue sections (approximately 5 × 5 mm) were excised from the interface between healthy and diseased tissues, surface-sterilized in 1% sodium hypochlorite for 60 s, rinsed three times with sterile distilled water, air-dried under aseptic conditions, and transferred onto potato sucrose agar (PSA) medium. Plates were incubated at 27 ± 2°C for 5–7 days following the isolation procedure described by (Sharma & Kulshrestha, 2015). Emerging fungal colonies were purified using the single-hyphal isolation technique to obtain pure cultures.

Preliminary identification of the fungal isolate was performed based on colony morphology and microscopic characteristics, including colony appearance, conidial morphology, hyphae, conidiophores, and appressoria, following the taxonomic descriptions of (Sharma & Kulshrestha, 2015) and (Saini et al., 2016). The fungal isolate used throughout this study was obtained from the culture collection of the Plant Pathology Laboratory, Department of Plant Protection, Faculty of Agriculture, Universitas Lampung. This isolate had previously been identified as *Colletotrichum brevisporum* based on morphological characteristics and molecular identification through sequencing of the internal transcribed spacer (ITS) region using the ITS1 and ITS4 primer pair. The ITS sequence was deposited in GenBank under accession number PP101255, and the complete

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molecular identification procedure has been reported by (Akin et al., 2026).

The pathogen is referred to as *Colletotrichum brevisporum* throughout this manuscript because previous molecular characterization based on ITS sequencing demonstrated that the isolate, which had previously been regarded as *C. gloeosporioides* based on morphological characteristics, belongs to *C. brevisporum* (Akin et al., 2026). Because the isolate originated from a well-maintained laboratory culture collection and had already been authenticated through both morphological examination and molecular characterization, repeated molecular identification was considered unnecessary for the objectives of the present study. The primary objective of this research was to evaluate the antifungal efficacy of cinnamon leaf and turmeric rhizome extracts rather than to re-establish the taxonomic identity of the pathogen. Therefore, the previously authenticated isolate was used throughout all experiments to ensure methodological consistency and facilitate direct comparison with the previous characterization study.

2.2 Preparation of Culture Medium

Potato sucrose agar (PSA) was prepared by boiling 200 g peeled potatoes in 1 L distilled water for 30 min. The extract was filtered and supplemented with 20 g sucrose and 20 g agar. The medium pH was adjusted to 6.5 ± 0.2 before sterilization at 121°C for 15 min. After cooling to approximately 50°C, 1.4 mL lactic acid (25%) was added to suppress bacterial growth. Approximately 20 mL medium was poured into each sterile 90-mm Petri dish. Each Petri dish represented one experimental unit in the in vitro assays. Extraction procedures were adapted from (Akin et al., 2024) and (Cruz et al., 2024).

2.3 Preparation of Cinnamon Leaf and Turmeric Rhizome Extracts

Fresh cinnamon leaves and turmeric rhizomes were washed, air-dried under shade conditions, and ground into fine powder. A total of 100 g of cinnamon leaf powder and 100 g of turmeric rhizome powder were separately macerated in 96% ethanol at a ratio of 1:10 (w/v) for 24 h with continuous stirring at room temperature. The extracts were filtered and concentrated using a rotary evaporator at 45°C until viscous crude extracts were obtained. The crude extracts were used directly for antifungal bioassays, and the extraction procedure was standardized for both plant materials to enable comparative evaluation of their biological activity. The crude extracts were re-dissolved in sterile distilled water containing 1% Tween-80 to obtain final concentrations of 0.25%, 0.50%, 0.75%, and 1.00% (w/v).

2.4 Experimental Design

The concentration range (0.25–1.00%) was selected based on previous studies reporting antifungal activity of cinnamon and turmeric extracts against phytopathogenic fungi (He et al., 2018; Karlina et al., 2024) Experiments were arranged in a Completely Randomized Design (CRD) with ten treatments: P0 (Control, 0.0% concentration), P1 (Propineb fungicide, 0.28%), P2 (Cinnamon leaf extract, 0.25% concentration), P3 (Cinnamon leaf extract, 0.50% concentration), P4 (Cinnamon leaf extract, 0.75% concentration), P5 (Cinnamon leaf extract, 1.0% concentration), P6 (Turmeric rhizome extract, 0.25% concentration), P7 (Turmeric rhizome extract, 0.50% concentration), P8 (Turmeric rhizome extract, 0.75% concentration), and P9 (Turmeric rhizome extract, 1.0% concentration). Each treatment was replicated four times.

Propineb (0.28%) was included as a positive control because it is a broad-spectrum dithiocarbamate fungicide commonly used for the management of anthracnose and other fungal diseases in fruit crops. Propineb acts by disrupting multiple enzymatic systems through interaction with sulfhydryl groups, thereby inhibiting fungal growth and development.

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For the in vitro assays, one Petri dish containing a single fungal colony constituted one experimental unit, resulting in a total of 40 experimental units (10 treatments × 4 replicates). For the in vivo assays, each replicate consisted of three papaya fruits receiving the same treatment, resulting in twelve fruits per treatment (4 replicates × 3 fruits) and a total of 120 fruits. The mean value of the three

2.5 In Vitro Mycelial Growth Assay

Extract-amended PSA medium was prepared by incorporating each treatment into molten medium before pouring. A 5-mm diameter mycelial plug taken from the actively growing margin of a 7-day-old culture was placed centrally on each plate. Antifungal activity was evaluated using the poisoned food technique as described by (Grover & Moore, 1962). Plates were incubated at 27 ± 2°C for 14 days. Colony diameter was measured daily in four perpendicular directions and averaged. Colony diameter was calculated as the average of four perpendicular measurements (Kai et al., 2019):

$$I = \frac{Dc - Dt}{Dc} x\ 100\%$$

where:
I = percentage inhibition of mycelial growth,
Dc = mean colony diameter in the untreated control,
Dt = mean colony diameter in the treated plates.

2.6 Spore Germination Assay

Conidial germination was assessed according to the procedure described by (Alvindia et al., 2022). Conidial suspensions were prepared from 14-day-old cultures of *Colletotrichum brevisporum* by adding 10 mL of sterile distilled water to each plate and gently scraping the colony surface with a sterile loop. The suspension was filtered through sterile cheesecloth to remove mycelial fragments and adjusted to 1 × 10^6 conidia mL^{-1} using a haemocytometer. An equal volume of conidial suspension and each treatment solution was mixed in sterile microtubes and incubated at 27 ± 2°C for 24 h under laboratory conditions. Sterile distilled water served as the negative control (P0), and propineb fungicide (0.28%) was used as the positive control (P1). After incubation, a drop of the mixture was placed on a glass slide and observed under a light microscope. A conidium was considered germinated when the germ tube length was equal to or greater than the diameter of the conidium. For each replicate, at least 100 conidia were observed randomly.

Spore germination was expressed as the proportion of germinated conidia relative to the total number of observed conidia. The inhibition of germination was determined by comparing each treatment with the control. Data of inhibition of germination were analyzed using analysis of variance (ANOVA) under a Completely Randomized Design at α = 0.05. When significant differences were detected, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$

2.7 In Vivo Fruit Assay

Healthy, uniform, mature-green papaya fruits were surface-sterilized with 1% sodium hypochlorite for 10 min, rinsed, and dried. Fruits were immersed in treatment solutions for 5 min and air-dried.

Each fruit was wounded (3 mm depth × 3 mm diameter) at one site and inoculated with 20 µL of a 1 × 10^6 conidia mL^{-1} suspension. Fruits were incubated at 27 ± 2°C and 90–95% relative humidity. Disease severity and incidence were recorded daily for six days after inoculation (DAI). Disease incidence was calculated as the percentage of infected fruits relative to the total number of assessed fruits following the procedure described by (Sharma & Kulshrestha, 2015).

Disease severity was evaluated following the disease rating scale modified from (Sharma & Kulshrestha, 2015):

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$$DS = \frac{\sum(n\ x\ v)}{N\ x\ V}\ x\ 100\%$$

where:
DS = disease severity
ni = number of fruits in each severity category
vi = disease score
N = total fruits observed
V = maximum score

Disease severity was estimated based on the percentage of fruit surface area covered by anthracnose lesions. Severity classes were adapted from (Sharma & Kulshrestha, 2015), where lesion coverage was visually estimated relative to the total fruit surface area. Disease severity was assessed using a five-scale rating system:
0 = no visible symptoms
1 = lesion covering <10% of fruit surface
2 = 10–25% lesion coverage
3 = 26–50% lesion coverage
4 = >50% lesion coverage

2.8 Scanning Electron Microscopy (SEM) Observation

Scanning electron microscopy (SEM) was performed to observe morphological alterations of *Colletotrichum brevisporum* following treatment with cinnamon leaf and turmeric rhizome extracts. Fungal cultures were grown in Potato Dextrose Broth (PDB) supplemented with the respective plant extracts and incubated at 27 ± 2 °C for 7 days under continuous shaking. Untreated fungal cultures grown in PDB without plant extract served as the control.

After incubation, the fungal biomass was collected by filtration and prepared for SEM analysis following the standard protocol of the Integrated Laboratory of the University of Lampung (LTSIT, Universitas Lampung). Samples were chemically fixed, dehydrated through a graded ethanol series, dried, sputter-coated with gold, and examined using a scanning electron microscope. Morphological changes in hyphae and conidia, including surface deformation, shrinkage, collapse, and structural disruption, were qualitatively compared between treated and untreated samples. SEM observations were used to provide supportive visual evidence of the antifungal effects of the plant extracts and were not subjected to statistical analysis.

2.9 Data analysis

All data were analyzed using analysis of variance (ANOVA) under a Completely Randomized Design (CRD) at a significance level of $\alpha = 0.05$. Percentage data were subjected to arcsine square-root transformation prior to analysis to satisfy the assumptions of normality and homogeneity of variance. When significant treatment effects were detected, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$. Linear regression analysis was conducted to evaluate the relationship between extract concentration and colony diameter, and the coefficient of determination (R^2) was used to assess the goodness-of-fit of the regression model.

3. Results and Discussion

3.1 Morphological Characterization and Pathogenicity Confirmation of the Anthracnose Pathogen

The fungal isolate used in this study was obtained from the culture collection of the Plant Pathology Laboratory, Department of Plant Protection, Faculty of Agriculture, Universitas Lampung. The isolate had previously been identified as *Colletotrichum brevisporum* based on morphological characteristics and internal transcribed spacer (ITS) sequence analysis, as reported by (Akin et al., 2026). Morphologically, the isolate produced grayish-white colonies with orange conidial masses and cylindrical, hyaline conidia with rounded ends, consistent with the characteristics previously described for *C. brevisporum* (Figure 1). Therefore, the previously characterized isolate was used in all subsequent antifungal assays. The detailed molecular identification procedure and ITS sequence accession number have been reported previously by (Akin et al., 2026).

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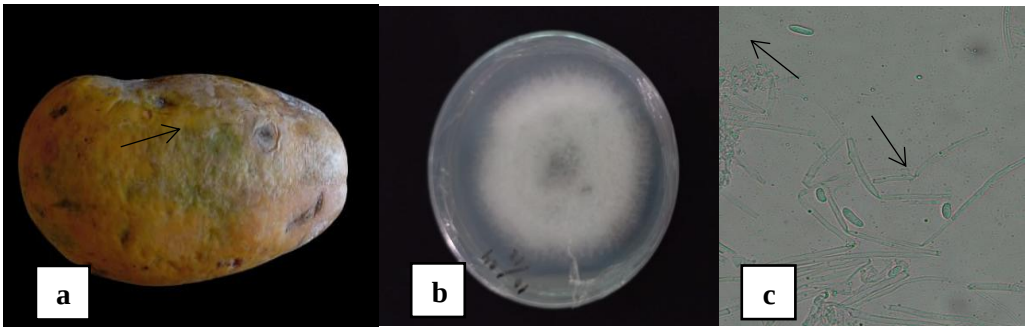

Figure 1. Anthracnose disease on papaya fruit: (a) anthracnose symptoms on papaya fruit, (b) colony morphology of *Colletotrichum brevisporum* on potato sucrose agar (PSA), and (c) hyphae and conidia of *C. brevisporum*.

Pathogenicity of the isolate was confirmed by artificial inoculation onto healthy papaya fruits. Typical anthracnose symptoms developed as small, circular, water-soaked lesions that gradually enlarged and became dark brown under humid conditions. White mycelial growth subsequently appeared on the lesion surface. The fungus was successfully re-isolated from symptomatic tissues, and microscopic observations revealed morphological characteristics identical to those of the original isolate, including hyaline aseptate conidia, septate hyphae, conidiophores, and appressoria (Figure 2). These results fulfilled Koch's postulates and confirmed that the isolate was pathogenic to papaya fruit.

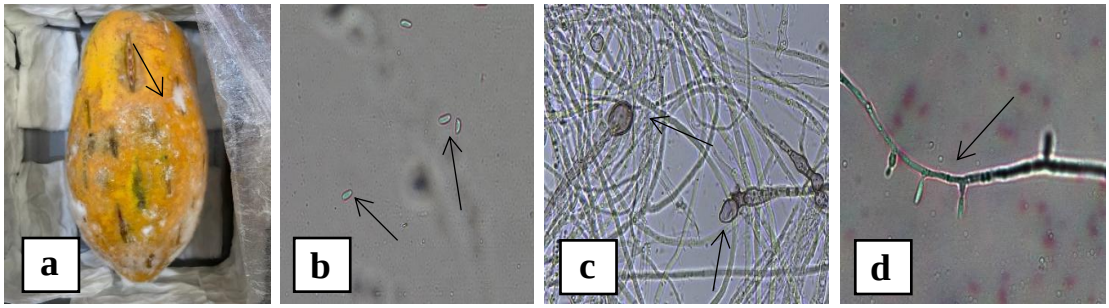

Figure 2. The results of pathogenicity test of *Colletotrichum brevisporum* on papaya fruit: (a) anthracnose symptoms following artificial inoculation, (b) conidia**,** (c) appressorium, and (d) conidiophore.

3.2 In Vitro Antifungal Activity of Cinnamon and Turmeric Extracts on Colony Growth

Analysis of variance revealed that both cinnamon leaf and turmeric rhizome extracts significantly inhibited the mycelial growth of *Colletotrichum brevisporum* throughout the observation period (2–14 DAI) ($p < 0.05$) (Table 1). Colony diameter decreased progressively with increasing extract concentration, indicating a clear concentration-dependent antifungal effect.

Among all treatments, turmeric rhizome extract consistently produced greater inhibition of colony growth than cinnamon leaf extract at equivalent concentrations. The highest concentration of turmeric extract (1.00%) resulted in the smallest colony diameter throughout the experiment and exhibited antifungal activity comparable to that of the synthetic fungicide propineb. Cinnamon leaf extract also significantly reduced fungal growth compared with the untreated control but was generally less effective than turmeric extract.

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The untreated control showed the largest colony diameter at all observation times, whereas all extract treatments significantly suppressed fungal growth. Representative colony morphology after 14 days of incubation is presented in Figure 3, while detailed colony diameter measurements are shown in Table 1.

Table 1. Effect of cinnamon leaf and turmeric rhizome extracts on colony diameter of *C. **brevisporum***

Treat-ment	Colony diameter of *C. brevisporum* (cm)						
	2 DAI	4 DAI	6 DAI	8 DAI	10 DAI	12 DAI	14 DAI
P0	2.15 ± 0.03 a	4.70 ± 0.04 a	6.90 ± 0.06 a	7.25 ± 0.05 a	7.37 ± 0.07 a	7.52 ± 0.06 a	7.52 ± 0.06 a
P1	1.88 ± 0.03 bc	3.55 ± 0.03 c	4.35 ± 0.09 cd	4.77 ± 0.11 d	4.77 ± 0.10 de	4.85 ± 0.10 de	4.88 ± 0.07 d
P2	1.97 ± 0.02 ab	3.70 ± 0.00 b	4.75 ± 0.03 b	5.20 ± 0.00 b	5.30 ± 0.06 b	5.32 ± 0.05 b	5.35 ± 0.03 b
P3	1.73 ± 0.07 cd	3.15 ± 0.03 de	4.15 ± 0.03 de	4.40 ± 0.06 e	4.57 ± 0.02 ef	4.65 ± 0.03 ef	4.65 ± 0.03 e
P4	1.71 ± 0.01 cd	3.20 ± 0.00 d	4.55 ± 0.03 bc	4.90 ± 0.06 cd	4.97 ± 0.05 cd	5.07 ± 0.02 c	5.10 ± 0.00 c
P5	1.73 ± 0.05 cd	3.10 ± 0.06 def	4.40 ± 0.00 c	5.05 ± 0.03 bc	5.05 ± 0.03 c	5.05 ± 0.03 cd	5.05 ± 0.03 cd
P6	1.70 ± 0.00 cd	3.00 ± 0.00 f	4.00 ± 0.00 e	4.42 ± 0.02 e	4.50 ± 0.00 f	4.60 ± 0.00 f	4.60 ± 0.00 e
P7	1.56 ± 0.04d	3.05 ± 0.03 ef	3.50 ± 0.00 f	3.80 ± 0.00 g	3.85 ± 0.03 h	3.95 ± 0.03 h	3.95 ± 0.03 g
P8	1.25 ± 0.05e	2.82 ± 0.01 g	3.40 ±0.07 fg	4.10 ± 0.06 f	4.20 ± 0.00 g	4.25 ± 0.03 g	4.25 ± 0.03 f
P9	0.98 ± 0.05f	2.55 ± 0.03 h	3.25 ± 0.03 g	3.75 ± 0.03 g	3.90 ± 0.00 h	4.00 ± 0.00 h	4.00 ± 0.00 g
HSD	0.19	0.14	0.21	0.25	0.24	0.21	0.18

Note*:* Means followed by the same letter within a column are not significantly different according to Tukey's HSD test at $p \leq 0.05$. DAI = days after inoculation. P0 = 0% (control); P1 = propineb 0.28%; P2–P5 = cinnamon leaf extract (0.25–1.00%); P6–P9 = turmeric rhizome extract (0.25–1.00%)

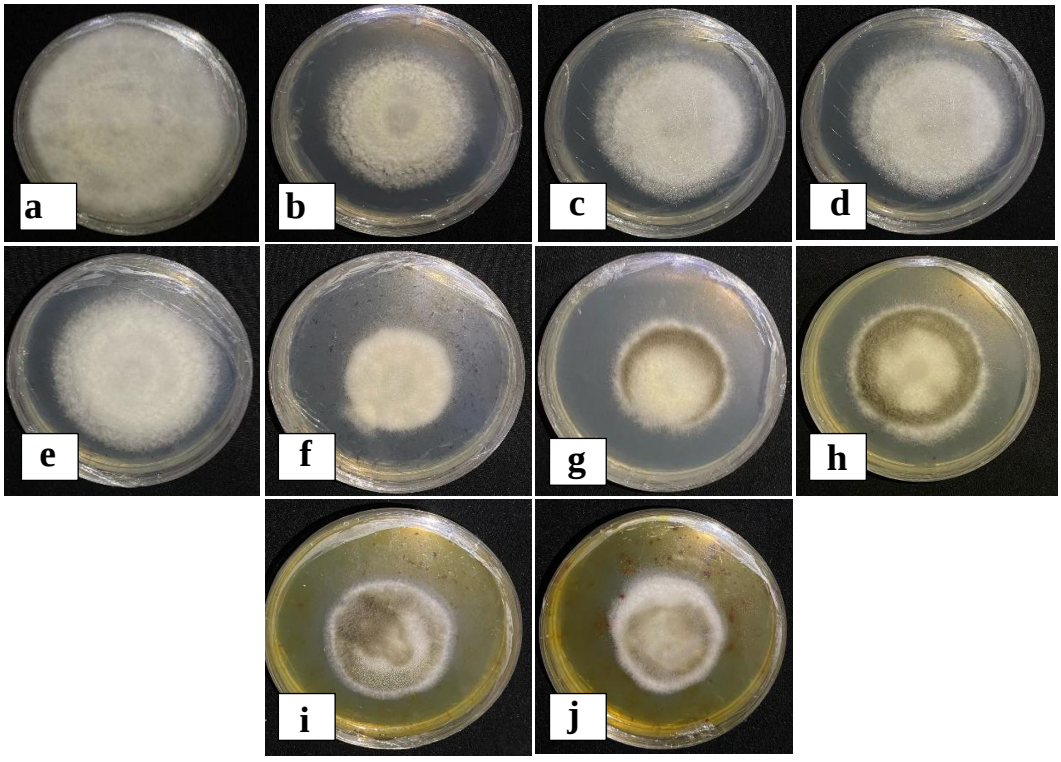

Figure 3. Effect of cinnamon leaf and turmeric rhizome extracts on *C. brevisporum* colony growth at 14 d: (a) P0 = 0%, (b) P1 = propineb 0.28%, (c) P2 = cinnamon 0.25%, (d) P3 = cinnamon 0.50 %, (e) P4 = cinnamon 0.75 %, (f) P5 = cinnamon 1.00 %, (g) P6 = turmeric 0.25%, (h) P7 = turmeric 0.50%, (i) P8 = turmeric 0.75%, (j) P9 = turmeric 1.00%.

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Scanning electron microscopy revealed marked structural alterations in fungal hyphae following treatment with both botanical extracts (Figure 4). Cinnamon leaf extract caused deformation of the hyphal surface, disruption of the cell wall, and surface roughening. In contrast, turmeric rhizome extract induced more extensive structural damage, including severe hyphal collapse, cell lysis, and fragmentation. These observations indicate that both extracts impaired fungal cell integrity, with turmeric extract producing more pronounced ultrastructural damage than cinnamon extract.

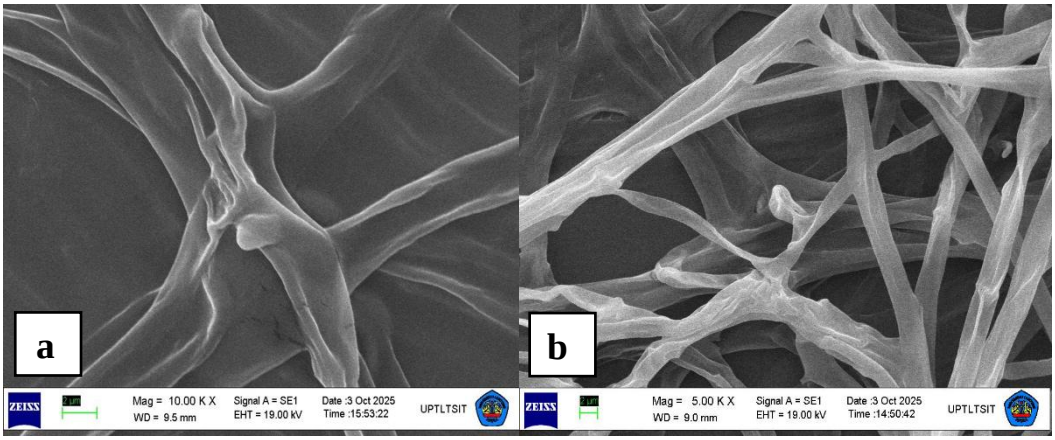

Figure 4. Scanning Electron Microscopy observations of *C. brevisporum* after extract treatment: (a) cinnamon extract caused cell wall disruption and deformation of hyphae; (b) turmeric extract caused more severe cell lysis and hyphal collapse. These SEM observations confirm structural damage leading to fungal growth inhibition.

The stronger inhibitory activity of turmeric extract observed in this study may also reflect the synergistic interaction among multiple secondary metabolites rather than the action of a single antifungal compound. Curcuminoids, particularly curcumin, together with sesquiterpenes such as ar-turmerone and curlone, have been reported to interfere with fungal membrane permeability, mitochondrial respiration, and oxidative balance, ultimately disrupting normal hyphal development (El-Saadony et al., 2025). Synergistic interactions among these metabolites may explain why turmeric extract consistently outperformed cinnamon leaf extract throughout the incubation period. In addition, damage to fungal membranes may facilitate further penetration of other bioactive constituents into the cytoplasm, thereby amplifying antifungal activity. Such synergistic mechanisms are increasingly recognized as an important advantage of crude botanical extracts over purified single compounds because multiple metabolites simultaneously target different physiological processes within fungal cells.

3.3 Effect of Cinnamon Leaf and Turmeric Rhizome Extracts on Spore Germination

Analysis of variance showed that cinnamon leaf and turmeric rhizome extracts significantly inhibited the germination of *Colletotrichum brevisporum* conidia compared with the untreated control ($p \leq 0.05$) (Table 2). The untreated control exhibited the highest spore germination, whereas all botanical extract treatments and the propineb fungicide significantly suppressed conidial germination. According to Tukey's HSD test, no significant differences were detected among the extract treatments and propineb, indicating comparable inhibitory effects on conidial germination.

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Although slight numerical variation was observed at the lowest extract concentration (0.25%), these differences were not statistically significant according to Tukey's HSD test, and all treatments at 0.50% and above resulted in near-complete inhibition (Table 2).

Microscopic observations supported these results (Figure 5). Conidia in the untreated control germinated normally and produced elongated germ tubes (Figure 5a). In contrast, conidia treated with cinnamon leaf or turmeric rhizome extracts showed either complete inhibition of germination or severely restricted germ tube development (Figure 5b–c), confirming the inhibitory effect of both botanical extracts on the early developmental stage of *C. brevisporum*.

Inhibition of conidial germination is particularly important from an epidemiological perspective because germination represents the earliest stage of host infection. Once germ tubes emerge, the pathogen rapidly forms an appressoria that facilitates penetration through the fruit cuticle. Therefore, suppression of spore germination may substantially reduce the probability of successful infection before tissue colonization occurs. This mechanism may explain why treatments exhibiting almost complete inhibition of conidial germination also resulted in lower disease severity during fruit storage. Consequently, botanical extracts capable of preventing spore germination could serve as preventive rather than curative agents within integrated postharvest disease management strategies.

Table 2. Effect of cinnamon leaf and turmeric rhizome extracts on conidial germination of *Colletotrichum brevisporum*

Treatment	Spore Germination
P0 (Control, 0.0% concentration)	0.93 ± 0.03 a
P1 (Propineb fungicide, 0.28%)	0.00 ± 0.00 b
P2 (Cinnamon leaf extract, 0.25% concentration)	0.07 ± 0.03 b
P3 (Cinnamon leaf extract, 0.50% concentration)	0.00 ± 0.00 b
P4 (Cinnamon leaf extract, 0.75% concentration)	0.00 ± 0.00 b
P5 (Cinnamon leaf extract, 1.0% concentration)	0.00 ± 0.00 b
P6 (Turmeric rhizome extract, 0.25% concentration)	0.07 ± 0.03 b
P7 (Turmeric rhizome extract, 0.50% concentration)	0.03 ± 0.03 b
P8 (Turmeric rhizome extract, 0.75% concentration)	0.00 ± 0.00 b
P9 (Turmeric rhizome extract, 1.0% concentration)	0.00 ± 0.00 b
HSD	0.106

Note: Means followed by the same letter within a column are not significantly different according to Tukey's HSD test at $p \leq 0.05$. DAI = days after inoculation.

Although numerical variation was observed among concentrations ranging from partial inhibition at 0.25% to complete inhibition at higher concentrations statistically these treatments showed comparable inhibitory effects. Microscopic observations further supported these results (Figure 5). In the control treatment, conidia germinated normally and produced elongated germ tubes (Figure 5a). In contrast, conidia exposed to cinnamon and turmeric extracts exhibited suppressed or abnormal germ tube development (Figure 5b–c), indicating strong inhibitory activity.

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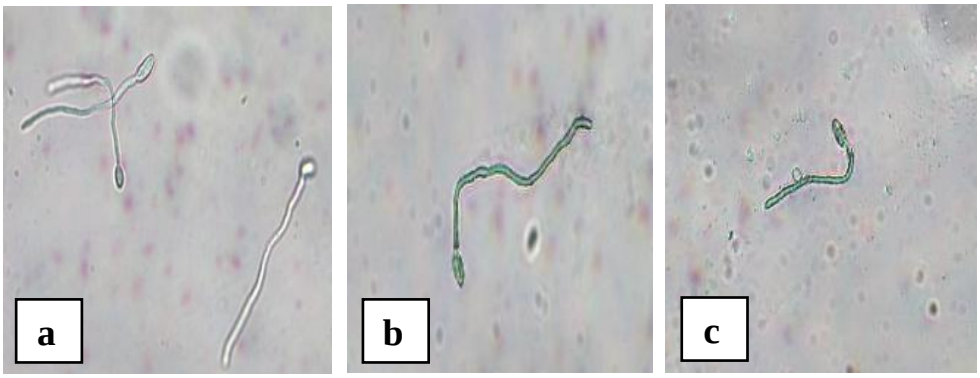

Figure 5. Effect of cinnamon leaf and turmeric rhizome extracts on conidial germination of *Colletotrichum brevisporum*: (a) untreated control showing normal conidial germination and germ tube development; (b) cinnamon leaf extract treatment showing suppressed germination; and (c) turmeric rhizome extract treatment showing complete or severely restricted conidial germination

3.4 Effect of Cinnamon and Turmeric Extracts on Anthracnose Severity and Incidence in Papaya Fruit

Analysis of variance showed that cinnamon leaf and turmeric rhizome extracts significantly affected anthracnose severity throughout the observation period ($p < 0.05$) (Table 3). Disease severity increased progressively in all treatments; however, fruits treated with botanical extracts consistently exhibited lower severity than the untreated control. Among the tested botanicals, turmeric rhizome extract produced greater suppression of disease severity than cinnamon leaf extract at equivalent concentrations. The highest concentration of turmeric extract (1.00%) resulted in the lowest disease severity among the botanical treatments and showed the closest performance to the propineb fungicide.

Table 3. Effect of cinnamon and turmeric extracts on anthracnose severity in papaya (%)

Treat-ment	Disease severity (%)				
	2 DAI	3 DAI	4 DAI	5 DAI	6 DAI
P0	6.36 ± 0.25 a	7.02 ± 0.89 a	8.66 ± 0.00 a	10.00 ± 0.00 a	10.00 ± 0.00 a
P1	2.50 ± 0.00 c	0.00 ± 0.00 c	3.54 ± 0.00 e	3.54 ± 0.00 e	3.54 ± 0.00 c
P2	4.33 ± 0.00 b	5.59 ± 0.00 ab	7.91 ± 0.00 b	9.68 ± 0.00 a	9.68 ± 0.00 ab
P3	4.33 ± 0.00 b	4.66 ± 0.33 ab	7.91 ± 0.00 b	9.35 ± 0.00 ab	9.35 ± 0.00 ab
P4	4.27 ± 0.73 b	5.56 ± 0.56 ab	7.07 ± 0.00 c	9.35 ± 0.00 ab	9.52 ± 0.17 ab
P5	2.50 ± 0.00 c	0.00 ± 0.00 c	3.54 ± 0.00 e	8.10 ± 0.19 bc	9.17 ± 0.51 ab
P6	2.50 ± 0.00 c	6.61 ± 0.00 ab	8.29 ± 0.37 ab	9.68 ± 0.00 a	9.68 ± 0.00 ab
P7	3.54 ± 0.00 bc	5.80 ± 0.81 ab	7.91 ± 0.00 b	7.86 ± 0.79 c	7.98 ± 1.37 ab
P8	3.54 ± 0.00 bc	4.33 ± 0.00 b	6.12 ± 0.00 d	7.91 ± 0.00 bc	8.63 ± 0.72 ab
P9	0.00 ± 0.00 d	0.00 ± 0.00 c	2.50 ± 0.00 f	5.59 ± 0.00 d	6.54 ± 0.96 bc
HSD	1.36	2.42	0.66	1.45	3.36

Note: Means followed by the same letter within a column are not significantly different according to Tukey's HSD test at $p \leq 0.05$. DAI = days after inoculation. P0 = 0% (control); P1 = propineb 0.28%; P2–P5 = cinnamon leaf extract (0.25–1.00%); P6–P9 = turmeric rhizome extract (0.25–1.00%)

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Visual observations were consistent with the quantitative disease severity data (Figure 6). The untreated control exhibited extensive lesion expansion and abundant mycelial growth, whereas disease symptoms were progressively reduced with increasing concentrations of both botanical extracts. Turmeric rhizome extract at higher concentrations produced visibly smaller lesions than cinnamon leaf extract at the same concentrations, while propineb remained the most effective treatment in suppressing symptom development.

Although turmeric extract substantially reduced disease severity, its efficacy remained lower than that of propineb during the later stages of disease development. This observation suggests that crude botanical extracts may undergo gradual degradation on fruit surfaces due to oxidation, volatilization of active constituents, or interactions with fruit exudates, resulting in reduced persistence over time. In contrast, synthetic fungicides are generally formulated to maintain biological activity for longer periods. Therefore, repeated application or improved formulations may be required to achieve prolonged protection when botanical extracts are used under commercial postharvest conditions.

In addition, *Colletotrichum* infections are presumed to frequently establish latent infections before symptom expression becomes visible. Once the pathogen has penetrated host tissues, externally applied botanical compounds may have limited ability to reach fungal hyphae growing beneath the fruit epidermis. Consequently, although the extracts effectively suppressed early fungal development and reduced disease progression, complete disease control was not achieved. This limitation highlights the importance of applying botanical fungicides before or immediately after harvest to maximize their protective efficacy.

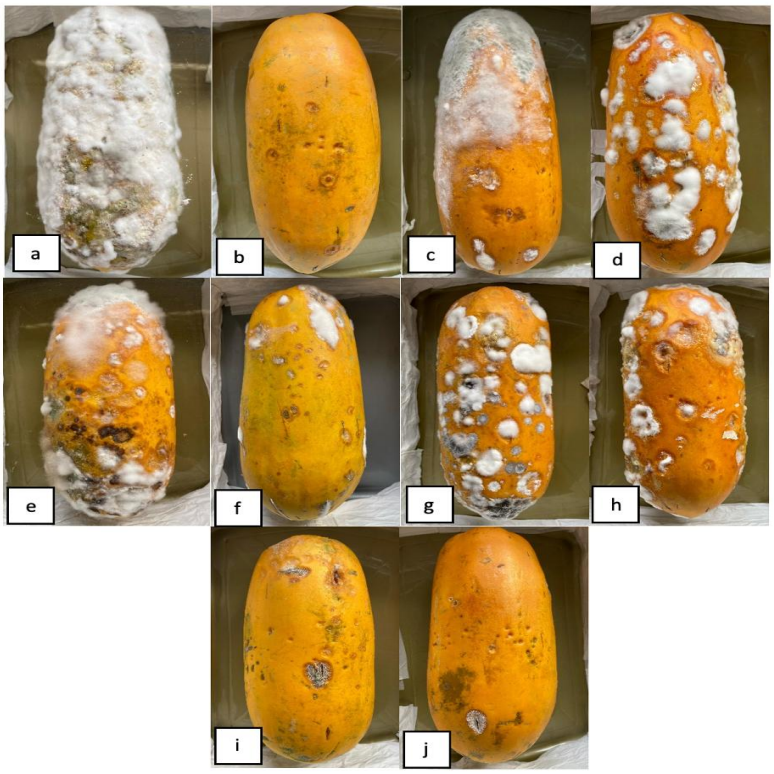

Figure 6. Anthracnose symptom development on papaya fruits at 6 days after inoculation (DAI): (a) untreated control; (b) propineb (0.28%); (c–f) cinnamon leaf extract at increasing concentrations (0.25, 0.50, 0.75, and 1.00%); and (g–j) turmeric rhizome extract at the same increasing concentrations.

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Analysis of variance also demonstrated that the treatments significantly affected disease incidence at all observation times ($p < 0.05$) (Table 4). Similar to disease severity, disease incidence was highest in the untreated control and significantly reduced by both botanical extracts and the propineb fungicide. Turmeric rhizome extract consistently resulted in lower disease incidence than cinnamon leaf extract at equivalent concentrations, particularly at 0.75% and 1.00%, although propineb provided the greatest reduction in disease incidence throughout the experiment.

Table 4. Effect of cinnamon and turmeric extracts on anthracnose incidence in papaya

	Disease incidence (%)				
Treatment	**2 DAI**	**3 DAI**	**4 DAI**	**5 DAI**	**6 DAI**
P0	7.87 ± 0.79 a	8.66 ± 0.00 a	8.66 ± 0.00 a	10.00 ± 0.00 a	10.00 ± 0.00 a
P1	5.00 ± 0.00 b	5.00 ± 0.00 c	5.00 ± 0.00 c	5.00 ± 0.00 d	5.00 ± 0.00 d
P2	7.07 ± 0.00 a	7.07 ± 0.00 ab	7.07 ± 0.00 ab	10.00 ± 0.00 a	10.00 ± 0.00 a
P3	5.00 ± 0.00 b	5.00 ± 0.00 c	7.07 ± 0.00 ab	10.00 ± 0.00 a	10.00 ± 0.00 a
P4	5.00 ± 0.00 b	6.04 ± 1.04 bc	7.07 ± 0.00 ab	8.66 ± 0.00 ab	10.00 ± 0.00 a
P5	5.00 ± 0.00 b	5.00 ± 0.00 c	5.00 ± 0.00 c	8.66 ± 0.00 ab	8.66 ± 0.00 b
P6	5.00 ± 0.00 b	7.07 ± 0.00 ab	8.66 ± 0.00 a	10.00 ± 0.00 a	10.00 ± 0.00 a
P7	5.00 ± 0.00 b	5.00 ± 0.00 c	8.66 ± 0.00 a	8.66 ± 0.00 ab	9.33 ± 0.67 ab
P8	5.00 ± 0.00 b	5.00 ± 0.00 c	6.04 ± 1.04 bc	7.87 ± 0.79 bc	8.66 ± 0.00 b
P9	0.00 ± 0.00 c	0.00 ± 0.00 d	5.00 ± 0.00 c	7.07 ± 0.00 c	7.07 ± 0.00 c
HSD	1.41	1.83	1.83	1.41	1.19

Note: Means followed by the same letter within a column are not significantly different according to Tukey's HSD test at $p \leq 0.05$. DAI = days after inoculation. P0 = 0% (control); P1 = propineb 0.28%; P2–P5 = cinnamon leaf extract (0.25–1.00%); P6–P9 = turmeric rhizome extract (0.25–1.00%)

The fungal isolate used in this study had previously been identified as *Colletotrichum brevisporum* through morphological characterization and ITS sequence analysis (Akin et al., 2026). The successful reproduction of anthracnose symptoms following artificial inoculation and subsequent re-isolation of the pathogen further confirmed its pathogenicity on papaya fruit, providing a reliable biological system for evaluating the antifungal efficacy of botanical extracts.

Both cinnamon leaf and turmeric rhizome extracts significantly inhibited fungal growth, suppressed conidial germination, and reduced anthracnose development on papaya fruit. The concentration-dependent inhibitory response observed in the present study indicates that increasing extract concentration enhanced antifungal efficacy. Similar concentration-dependent effects have been reported for several botanical extracts against *Colletotrichum* spp. (Akin et al., 2024; Sudirga et al., 2024). Among the tested botanicals, turmeric rhizome extract consistently exhibited stronger antifungal activity than cinnamon leaf extract under both *in vitro* and *in vivo* conditions, suggesting that turmeric contains more potent antifungal constituents under the extraction conditions employed in this study.

The superior antifungal activity of turmeric rhizome extract agrees with previous studies demonstrating its effectiveness against *Colletotrichum* spp. (Alvindia et al., 2022) reported that turmeric crude extract effectively inhibited *C. brevisporum* causing mango anthracnose by suppressing mycelial growth, inhibiting spore germination, and reducing disease development. The antifungal activity was

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attributed to major bioactive constituents, including ar-turmerone, curlone, α-curcumene, and curcuminoids, which interfere with fungal growth and cellular integrity.

However, the present findings differ from several previous reports in which cinnamon-derived products exhibited stronger antifungal activity than turmeric. For example, (He et al., 2018) and (Darshan et al., 2019) demonstrated that cinnamon bark extracts and essential oils rich in cinnamaldehyde completely inhibited the growth of *Colletotrichum* spp. The discrepancy between those studies and the present work is likely attributable to differences in the plant organs used, extraction methods, solvent systems, and concentrations of bioactive compounds. Unlike cinnamon bark, cinnamon leaves generally contain lower concentrations of cinnamaldehyde and relatively higher proportions of eugenol and other phenolic compounds (Martinko & Mioč, 2024), which may explain their comparatively lower antifungal efficacy observed in this study. Nevertheless, the significant inhibition of *C. brevisporum* by cinnamon leaf extract observed in the present study is consistent with the broad-spectrum antimicrobial properties previously reported for *Cinnamomum burmannii*. (Martinko & Mioč, 2024) demonstrated that cinnamon bark extract effectively inhibited the phytopathogenic fungus *Fusarium sporotrichioides*, whereas (Li et al., 2025) reported that cinnamaldehyde markedly suppressed the growth of *Phytophthora nicotianae* by disrupting membrane permeability, inhibiting essential enzymatic activities, and impairing hyphal development. Comparable mechanisms have also been reported against bacterial pathogens, where *C. burmannii* extract inhibited microbial growth and biofilm formation through membrane disruption and leakage of intracellular components (Panjaitan et al., 2022). These findings indicate that cinnamon-derived bioactive compounds possess broad-spectrum antimicrobial activity through multiple mechanisms targeting membrane integrity and cellular metabolism, supporting the antifungal activity of cinnamon leaf extract observed in the present study despite its lower efficacy compared with turmeric rhizome extract.

Although both botanical extracts exhibited strong antifungal activity under *in vitro* conditions, disease suppression on papaya fruit was comparatively lower. Similar discrepancies between laboratory assays and *in vivo* experiments have frequently been reported for plant-derived antifungal compounds because environmental conditions, host-pathogen interactions, compound degradation, limited persistence on fruit surfaces, and reduced penetration into infected tissues may decrease antifungal effectiveness under practical conditions (Andrade-Hoyos et al., 2025; Wang et al., 2023). These findings suggest that results obtained under laboratory conditions should be interpreted cautiously when predicting field or postharvest performance.

Despite the promising antifungal activity of turmeric rhizome extract, propineb consistently provided greater disease suppression during the later stages of storage. This difference is expected because propineb is a multisite contact fungicide specifically formulated to maintain stability and persistence on fruit surfaces, allowing prolonged protection against pathogen development. In contrast, crude botanical extracts may undergo oxidation, volatilization, or degradation during storage, reducing the availability of active compounds over time. These observations suggest that improving formulation stability, rather than simply increasing extract concentration, will be essential to enhance the practical performance of turmeric extract under commercial postharvest conditions.

The antifungal activity observed in this study is likely associated with the presence of bioactive secondary metabolites. Turmeric

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rhizomes contain curcuminoids, ar-turmerone, curlone, α-curcumene, and other sesquiterpenes, whereas cinnamon leaves contain cinnamaldehyde, eugenol, and various phenolic compounds. These metabolites have been reported to disrupt fungal cell membranes, increase membrane permeability, inhibit essential enzymatic processes, induce leakage of intracellular constituents, and ultimately suppress fungal growth (Bui et al., 2021; He et al., 2018; Sudirga et al., 2024; Wang et al., 2023). The scanning electron microscopy observations obtained in the present study provide direct morphological evidence supporting these mechanisms. Untreated hyphae exhibited smooth, intact, and cylindrical structures, whereas hyphae exposed to cinnamon leaf extract showed surface deformation, cell wall disruption, and irregular surface morphology. More extensive ultrastructural damage was observed following treatment with turmeric rhizome extract, including severe hyphal collapse, cell lysis, and fragmentation. The greater degree of structural damage induced by turmeric extract is consistent with its stronger inhibition of mycelial growth, complete suppression of conidial germination at higher concentrations, and greater reduction of anthracnose severity compared with cinnamon leaf extract. These observations indicate that impairment of fungal cell integrity is a major mechanism underlying the antifungal activity of both botanical extracts. Similar ultrastructural alterations have been reported following exposure of phytopathogenic fungi to plant-derived antifungal compounds, where disruption of cell wall and plasma membrane integrity resulted in cytoplasmic leakage, loss of cellular organization, and irreversible inhibition of fungal growth (He et al., 2018; Martinko & Mioč, 2024).

The inhibition of conidial germination observed in this study is particularly important because conidial germination represents the critical transition from fungal dispersal to host infection. Germinating conidia rapidly produce germ tubes and differentiate appressoria, enabling penetration through the papaya cuticle and initiation of tissue colonization. Therefore, suppression of this early developmental stage may substantially reduce infection efficiency before extensive fungal growth occurs. This explains why treatments producing almost complete inhibition of conidial germination also resulted in lower disease severity during fruit storage. Consequently, botanical extracts may provide greater value as preventive protectants rather than curative treatments after infection has become established.

Beyond its biological efficacy, turmeric rhizome extract also demonstrates considerable potential for commercial application as a botanical fungicide. Turmeric is widely cultivated in Indonesia, relatively inexpensive, readily available throughout the year, and represents a renewable source of bioactive compounds. Compared with synthetic fungicides, turmeric-based products offer the potential to reduce chemical residues and environmental contamination while supporting more sustainable postharvest disease management. Nevertheless, successful commercialization will require further studies on formulation development, shelf-life stability, standardization of active compounds, large-scale efficacy evaluation, economic feasibility, and regulatory approval before adoption by growers and the postharvest industry.

Another important implication of the present findings relates to resistance management. Repeated application of synthetic fungicides with similar modes of action may accelerate the development of resistant pathogen populations. In contrast, botanical extracts generally contain multiple bioactive compounds that target several physiological processes simultaneously, thereby reducing the likelihood of rapid resistance development. Although this potential advantage requires further experimental validation, integrating turmeric-based botanical fungicides with

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conventional disease management strategies may help reduce selection pressure while contributing to more sustainable postharvest disease control.

Overall, turmeric rhizome extract exhibited stronger and more consistent antifungal activity than cinnamon leaf extract against *Colletotrichum brevisporum*. Although its efficacy remained lower than that of the synthetic fungicide propineb during advanced stages of disease development, the substantial inhibition of mycelial growth, conidial germination, and anthracnose development demonstrates its promise as an environmentally friendly component of integrated postharvest disease management. Future studies should focus on optimizing extract formulation, improving compound stability through advanced delivery systems such as nanoemulsions, standardizing phytochemical composition, and validating efficacy under commercial postharvest storage conditions.

From a broader perspective, the present findings contribute to the growing body of evidence supporting plant-derived products as sustainable alternatives to conventional fungicides for postharvest disease management. Botanical extracts generally contain complex mixtures of bioactive metabolites with multiple cellular targets, reducing the likelihood of rapid resistance development compared with single-site synthetic fungicides. Moreover, their biodegradable nature and lower environmental persistence make them attractive components of integrated disease management programs aimed at minimizing chemical inputs. Although additional studies on formulation, standardization, and commercial validation remain necessary, the comparative approach employed in this study provides valuable information for selecting the most promising botanical resources for future product development.

4. Limitations and Future Directions

Although this study demonstrated the superior antifungal efficacy of turmeric (*Curcuma longa*) rhizome extract compared with cinnamon (*Cinnamomum burmannii*) leaf extract against *Colletotrichum brevisporum* under both *in vitro* and *in vivo* conditions, several limitations should be acknowledged. First, the experiments were conducted under controlled laboratory and postharvest storage conditions using artificially inoculated papaya fruits; therefore, the results may not fully represent the variability encountered during commercial storage, transportation, and marketing. Second, antifungal activity was evaluated using a single, well-characterized isolate of *C. brevisporum*. Although the isolate had previously been authenticated through morphological characterization and ITS sequence analysis, additional isolates representing different geographic origins or genetic backgrounds should be evaluated to confirm the consistency and broader applicability of the observed antifungal effects. Third, the study evaluated crude ethanolic extracts without identifying or quantifying the specific bioactive compounds responsible for the observed antifungal activity. Consequently, the relative contribution of individual metabolites and possible synergistic interactions among extract constituents remains unclear. In addition, extraction yield (% recovery) was not determined, limiting comparisons of extraction efficiency and reproducibility between the two botanical extracts. Finally, the effectiveness of the extracts was assessed only during the early stages of postharvest storage, and their long-term stability and persistence were not investigated.

Future studies should evaluate the efficacy of cinnamon leaf and turmeric rhizome extracts under commercial postharvest handling and storage conditions using naturally infected fruits and multiple *C. brevisporum* isolates. Comprehensive phytochemical characterization, including GC–MS or LC–MS analysis, is needed to identify the major antifungal compounds responsible for disease suppression, quantify extraction yield, and facilitate product

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standardization. In addition, the development of advanced formulations, including nanoemulsions, nanoencapsulation, or edible coatings, should be explored to improve extract stability, prolong antifungal activity, and enhance practical application. These approaches will contribute to the development of sustainable botanical fungicides for the postharvest management of papaya anthracnose.

5. Conclusion

Both cinnamon leaf extract and turmeric rhizome extract exhibited significant antifungal activity against *Colletotrichum brevisporum* under both *in vitro* and *in vivo* conditions. Among the tested botanicals, turmeric rhizome extract consistently showed greater efficacy than cinnamon leaf extract, with the 1.00% concentration reducing mycelial growth by 46.84%, decreasing disease severity by 34.6%, and completely inhibiting conidial germination compared with the untreated control. Scanning electron microscopy further demonstrated that turmeric extract caused more severe ultrastructural damage to fungal hyphae than cinnamon extract, supporting its stronger antifungal activity. Collectively, these findings indicate that turmeric rhizome extract is a promising botanical antifungal candidate for integrated postharvest management of papaya anthracnose. However, this study was limited to the evaluation of crude extracts under controlled laboratory and postharvest storage conditions without phytochemical characterization, extraction yield determination, or validation under commercial storage systems. Therefore, further studies involving phytochemical characterization, formulation development, optimization of extraction procedures, and commercial-scale validation are required before turmeric rhizome extract can be recommended for practical postharvest disease management.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Authorship Contribution Statement

Titik Nur Aeny: conceptualization, methodology, investigation, formal analysis, data curation, writing original draft, supervision. Hasriadi Mat Akin: Methodology, validation, formal analysis, writing, review & editing. Selvi Helina: methodology, investigation, data curation, writing, review & editing. Zakiatun Nafsiyah: investigation, validation, writing review & editing. Fauziah Rizky Nurfadillah: investigation, data curation, visualization, writing, review & editing. All authors have read and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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