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Evaluating the Antifungal Efficacy of Cinnamon Oil for Controlling *Penicillium digitatum* and Enhancing Post-Harvest Orange fruit Preservation

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ABSTRACT

Penicillium digitatum is one of the major pathogens for green mold in citruses and is a serious threat for postharvest disease control. *P. digitatum* was isolated from the infected oranges, and pathogenicity tests were conducted. The most virulent isolate was then identified confirmed 100% is *P. digitatum* based on molecular analysis. The in vitro efficacy of Cinnamon oil was investigated using well diffusion and minimum inhibitory concentration assay. The findings confirmed that higher concentration (5%) had a significant inhibition 90% impact on fungal growth. The Gas chromatography–mass spectrometry (GC–MS) analysis showed 6 out of 29 compounds were present at highest concentrations; namely: 5H-1-Pyrindine-3-carbonitrile, 2-bromo-6,7-dihydro- (24.52%), 1-Methyl-1H-pyrazolo[3,4-b]pyridin-3-ylamine (24.25%), Tolmetin (13.9%), and Palmitic acid (8.82%), 6-Acetyl-6-indolo(2,3-b)quinoxaline (7.75%), 2,5-Ethano-2H-azocino[4,3-b]indole (7.65%). For the in vivo experiment, orange fruits were immersed in 1% Cinnamon oil to assess its efficacy in extending shelf life. Shelf life and infection reduction rate were observed for 22 days, which showed that Cinnamon oil prevents fungal infection, keeping the fruit healthy and free of contamination. These results indicate that Cinnamon oil can be a natural and eco-friendly substitute for chemical fungicides in plant disease management and food preservation.

1.Introduction

Post-harvest losses have always presented one of the main difficulties in agricultural industries. Most of the decay in the post-harvest category within citrus fruits results from fungal attacks hence highly affecting their quality and market value. The most frequent and devastating among various post-harvest diseases is the green mold brought about by *Penicillium digitatum (Pers.: Fr.) Sacc.*; this is one of the key culprits that ensures large economic loss all over the world (Ahima et al., 2019). About 30% of citrus fruits are lost due to spoilage during storage and marketing, which further aggravates the food insecurity and economic instability in many regions (Singh et al., 2021). Proper management of these post-harvest pathogens hence becomes highly important and underpins global attempts toward waste reduction and sustainable improvement in citrus production.

Application methods traditionally have focused on the use of synthetic chemical fungicides to control *P. digitatum*. Fungicides applied to date include Imazalil, Thiabendazole, and sodium bicarbonate and have been quite useful in the reduction of the fungal growth, which extends the shelf life of citrus fruits ((Martínez-Blay et al., 2020). However, this wide and long-term use of these chemicals has resulted in a number of issues. Residues of synthetic fungicides on fruits pose potential risks to human health, including carcinogenicity and endocrine disruption (Huang and Li, 2024). Also, with fungicide resistance acquired by the strain *P. digitatum*, its control with the application of chemicals does not yield substantial positive results anymore and necessitates seeking other friendly means that will bring minimal damage or injury (González-Estrada et al., 2019).

Attention in recent times has shifted to the use of eco-friendly and sustainable approaches as methods for biological control. In this regard, plant-derived essential oils have gained significant attention due to their broad-spectrum antimicrobial activity coupled with low toxicity and biodegradability (Kaur et al., 2025). Extracts from such plants like cinnamon, clove, and thyme have been developed for antifungal activity against a wide range of pathogens that include *P. digitatum* (Reis et al., 2023). Point to the fact that out of these, cinnamon oil worked its way up the ranks extremely slowly because it had higher content of those types of bioactive compounds-cinnamaldehyde and eugenol-accounting for disruption in the cell membranes and inhibition in enzymatic activities (Aroiee et al., 2022).

Several studies have demonstrated cinnamon oil's effectiveness in controlling fungal infections in fruits, with a notable reduction in the incidence of green mold in oranges compared to previously recorded levels (Hassan et al. (2022). In vitro tests revealed that Cinnamon oil emulsion inhibits growths of *P. digitatum* quite significantly (Sakthiguru et al., 2021). Thus, this presents promising potential as a natural preservative agent. However, the efficacy of Cinnamon oil still needed to be studied under in-vivo conditions for an understanding of the practical application during post-harvest management. The present study was aimed at determining the antifungal efficacy of Cinnamon oil against *P. digitatum* by using in vitro and in vivo assays.

2.Material and Methods

2.1. Penicillium digitatum isolation:

P. digitatum was isolated from the naturally infected fruits of orange (*Citrus sinensis*) that had visible green mold. Small pieces of infected tissues treated for surface sterilization with 1% sodium hypochlorite were washed in sterile distilled water and plated on sterile Petri dishes containing potato dextrose agar (PDA). The plates were incubated at 25°C for 5 days to allow the growth of fungi. Repeated subculturing by single spore was done on fresh PDA plates to obtain pure cultures. Morphological identification of fungal growth and structures was performed visually and through light microscopy (Niu et al., 2016).

2.2. Pathogenicity and molecular identification

Three *P. digitatum* isolates were obtained and pathogenicity was checked. Inoculation of healthy citrus fruits following the plug test method. One pore was made on the surface of fruits using a cork borer and one plug of *P. digitatum* was inserted into the pore. Symptoms had appeared after 5-7 days of incubation at 25°C. The ITS1 forward primer (5´TCC GTA

GGT GAA CCT TGC GG 3′) and ITS4 reverse primer (5′TCC TCC GCT TAT TGA TAT GC 3′) were used to amplify the ITS gene to identify selected fungi isolates. The obtained amplicons were sequenced and further compared with reference sequences obtained from the GenBank database for confirmation of the species (Rashid et al., 2025).

2.3. Cinnamon Oil Emulsion Preparation

Ceylon cinnamon sticks (*Cinnamomum verum*), known for their quality and unique smell, were purchased from local markets. The sticks were ground into a fine powder, then 100 grams of powdered cinnamon was added to a filter paper thimble and then positioned in the Soxhlet extractor (Drawell Analytical – China). The polar solvent applied for extraction was ethanol. The Soxhlet apparatus was fitted with a heating mantle to reflux the ethanol to temperature 100°C to allow efficient extraction of non-polar and polar compounds. The extraction was done for 5 hours. After completion, the solvent was evaporated under reduced pressure, resulting in a concentrated extract of cinnamon essential oil (Wong et al., 2014). The oil was carefully harvested and stored for use.

To prepare emulsions, the cinnamon oil isolated by extraction was blended with sterile distilled water as the water phase. A non-ionic surfactant, Tween 80, was incorporated at a concentration of 0.1% (v/v) as an emulsifier to stabilize the oil-in-water emulsion. Emulsions were prepared at various concentrations of the essential oil: 5%, 4%, 3%, 2%, and 1% (v/v). All the mixtures were vigorously shaken for 5 minutes to achieve uniform dispersion of the oil droplets in the aqueous phase, resulting in a stable and homogeneous emulsion.

2.4. In Vitro Antifungal Assay

The antifungal activity of cinnamon oil against *P. digitatum* was evaluated using the well-diffusion method (Rashid and Aziz, 2025). A five mm diameter plug of an actively growing culture of *P. digitatum* was placed in the center of PDA plates. Two wells of 5 mm diameter were aseptically created in the agar using a sterile cork borer. The wells were located on either side of the Petri dish, each 3 cm from the central fungal plug. Around 30 ml cinnamon oil emulsion was added, and 5 plates were used for each concentration. Control plates were inoculated with *P. digitatum* and the plates were incubated at 25°C for 5 days. The percentage inhibition of fungal growth was calculated using the formula:

$$\text{Percent Growth Inhibition} = \frac{\text{D control} - \text{D treatment}}{\text{Dcontrol}} \times 100$$

Where:

D control is the diameter of the fungal growth in the control

D treatment is the diameter of the fungal growth in the treatment

2.5. GC-MS Analysis of Cinnamon Oil

The Cinnamon oil was dissolved in the methanol at rate 1:10 (v:v) for GC-MS analyses. The crude extract was, filtered through a 0.22 µm syringe filter and then the purified oil was taken for analysis. GCMS (Shimadzu Corporation-Japan) system equipped with a capillary column for proper separation of compounds. The injector temperature was 250°C, and the oven temperature was set to start at 60°C and ramp at 10°C/min to 280°C. The oven was maintained at 280°C for 10 min for complete dissolution of all the compounds. Helium was used as the carrier gas since it is inert and offers high separation efficiency. The system was run under electron ionization mode at 70 eV and m/z range of 50 to 500 to detect a broad range of compounds.

2.6. In Vivo Test on Citrus Fruits

Fresh orange fruits were washed, surface-sterilized by swabbing with 70% ethanol and then air-dried. Artificial injuries were applied, to the skin of citrus fruits with the help of a sterile sharp needle 2 mm, non-injured fruits were also included for comparison with injured fruits. Each fruit sample was coated with a 1% emulsified cinnamon oil concentration until fully covered and visibly wet, left for air drying, inoculated with an already prepared *P. digitatum* spore suspension (1×10^6 spores/mL) after drying by spraying to full coating. Water was used as the negative control, while a (Imazalil) fungicide served as the positive control for comparison. Treated fruits were then kept at 25°C with 90% relative humidity for 22 days. Disease severity and weight loss were noted to determine the efficacy

of cinnamon oil as a protective agent. Five fruits were used per treatment with five replications.

2.7. Data Analysis

Statistical analysis of all experimental data was performed using one-way analysis of variance (ANOVA) in SPSS Statistics software (version 27.0, IBM Corp., Armonk, NY). Comparisons were performed by Tukey's Honestly Significant Difference (HSD) test to establish statistically significant pairwise differences between treatment groups at $\alpha = 0.05$.

3.Results and Discussion

3.1. Penicillium digitatum isolation and identification

Three fungal isolates were successfully obtained and purified from the collected samples. Pathogenicity tests confirmed that all three isolates were pathogenic after three to seven days of infection. To confirm Koch's postulates, each fungal isolate was re-isolated from infected fruit, while no fungi were recovered from the control samples. Among others, the most pathogenic one isolate C was selected for further experiments (Fig 1).

The selected isolate was identified through PCR amplification using universal primers. The amplified product produced a fragment of size 500 bp. A BLAST search in the NCBI database confirmed that the *P. digitatum* sequences of the isolate were 100% identical to *P. digitatum* strain (Pd1), with a GenBank accession number of (JZ351000.1). The sequence was deposited in NCBI and assigned an accession number (PV650922).

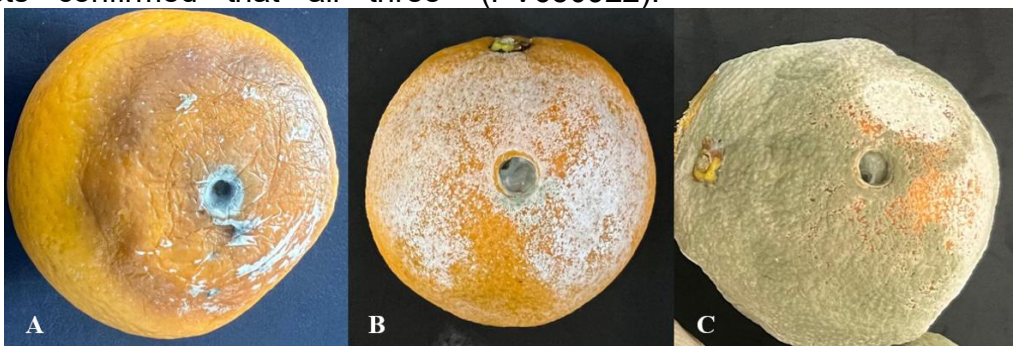

Fig 1. Pathogenicity test of *P. digitatum* isolates showed visible symptoms after 7 days (A, B and C: Isolates)

3.2 Antifungal Activity of Cinnamon Oil

The antifungal efficacy of cinnamon oil was evaluated using the well-diffusion method. Cinnamon oil suppressed 90% of fungal growth at a concentration of 5% (Fig 2), indicating an effective antifungal activity. This was followed by 4% concentration, which inhibited 58% of the fungal growth. The 3% concentration inhibited 33%, while the lowest inhibition rates were observed at 2% and 1% with 28% and 20% inhibition, respectively (Fig 3).

Earlier research has confirmed that cinnamon oil possesses high efficacy in inhibiting fungal growth. Specifically, cinnamon bark oil has been shown to disrupt the cell membranes of *P. digitatum* (Yang et al., 2021; Zhou et al., 2024), *Aspergillus flavus* and *P. citrinum* (Liu et al., 2024a), and *P. oxalicum* (Liu et al., 2024b).

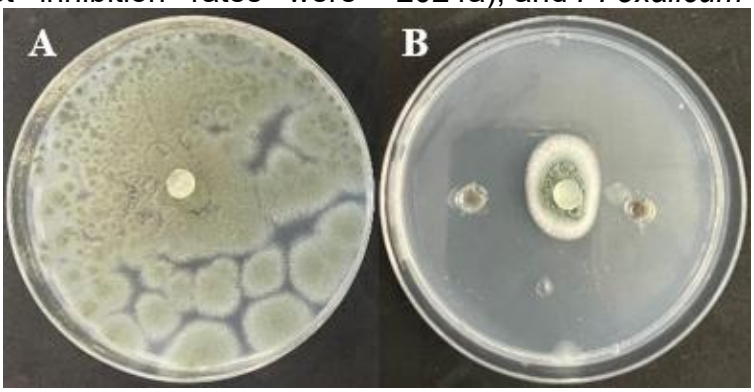

Fig 2. Antifungal activity of 5% cinnamon oil against *P. digitatum*. A: Control; B: Treated with cinnamon oil

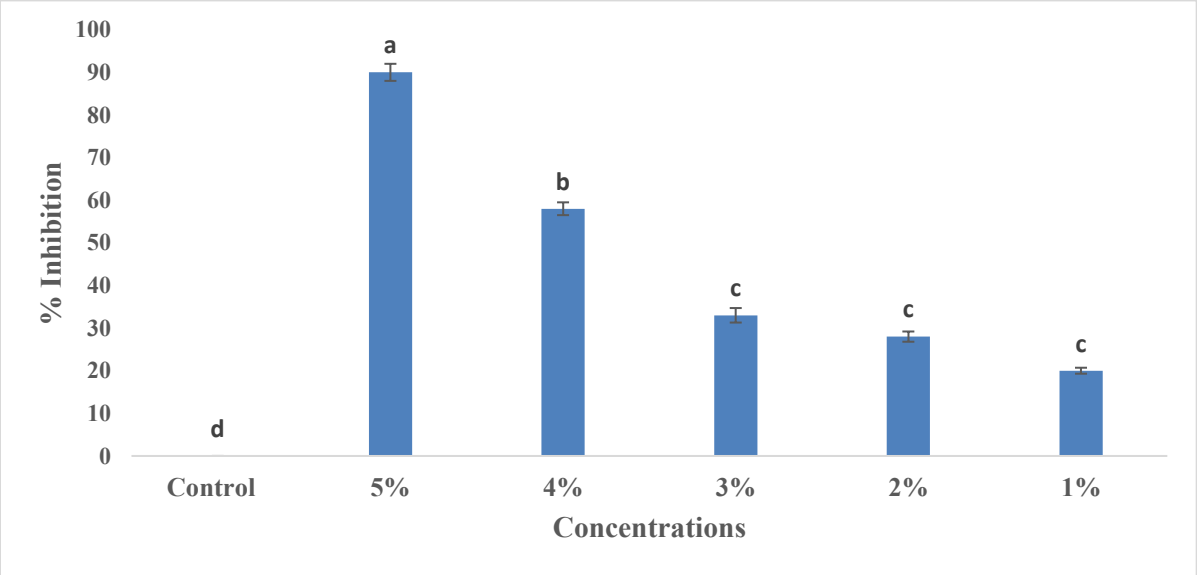

Fig3. Antifungal activity of different concentrations of cinnamon oil against *P. digitatum*.

3.3 GC-MS Analysis of Secondary Metabolites in Cinnamon Oil

GC-MS analysis of cinnamon oil revealed 29 compounds were identified among those, 6-Acetyl-6-indolo(2,3-b) quinoxaline (7.75%), 1-Methyl-1H-pyrazolo[3,4-b] pyridin-3-ylamine (24.25%), 5H-1-Pyrindine-3-carbonitrile, 2-bromo-6,7-dihydro (24.52%), Tolmetin (13.9%) and Palmitic acid (8.82%) (Fig 4). They are present in significant concentrations and may be involved in cinnamon oil's antifungal activity (Table 1).

Table 1. Major Bioactive Compounds Identified in Cinnamon Oil by GC-MS Analysis.

No.	Name	R. Time	Area %	Height %	Formula
1	Cyclotetrasiloxane	3.309	0.08	0.23	$H_8O_4Si^4$
2	4-(2-amino-1-hydroxypropyl)phenol	4.069	0.1	0.4	$C_{15}H_{29}NO_2Si_2$
3	3-Amino-5-bromo-2-chloropyridine	5.026	0.27	0.23	$C_5H_4BrClN_2$
4	6-Acetyl-6-indolo(2,3-b)quinoxaline	5.194	4.25	7.75	$C_{16}H_{11}N_3O$
5	5-[p-Methoxyphenyl]-2,4-pentadienoic acid	5.325	0.21	0.6	$C_{12}H_{12}O_3$
6	Plumbane, tetrakis(2-methylpropyl)-	5.433	0.05	0.07	$C_{16}H_{36}Pb$
7	2,2-Dimethyl-2,3,4,5,6,7-hexahydro-(1H)2-benzazoninium iodide	5.526	0.74	1.45	$C_{14}H_{22}IN$
8	Glutaric acid, cyclohexylmethyl 4-bromo-2-methoxyphenyl ester	5.672	0.51	0.5	$C_{19}H_{25}BrO_5$
9	1-Methyl-1H-pyrazolo[3,4-b]pyridin-3-ylamine	5.764	8.79	24.25	$C_{10}H_{16}N_4Si$
10	6-Phenyl-2-thiouracil	5.858	0.56	1.05	$C_{10}H_8N_2OS$
11	Labda-7,14-dien-13(R)-ol	6.034	1.2	3.46	$C_{20}H_{34}O$
12	5H-1-Pyrindine-3-carbonitrile	6.321	57.89	24.52	$C_9H_7BrN_2$
13	1,2,3,3a,4a,5,6,7,8,9,9a,9b-Dodecahydrocyclopenta[def]phenanthrene	6.471	0.55	0.9	$C_{15}H_{22}$

14	10-Chloro-9-vinylanthracene	6.552	0.87	0.82	$C_{16}H_{11}Cl$
15	Diglycolic acid, hexyl 2-octyl ester	6.753	0.26	0.25	$C_{18}H_{34}O_5$
16	2-Butenedioic acid, 2-(diisopropylamino)-, dimethyl ester	6.829	0.23	0.23	$C_{12}H_{21}NO_4$
17	Tolmetin	7.0	6.08	13.9	$C_{15}H_{15}NO_3$
18	Benz[a]anthracene,	7.182	0.01	0.04	$C_{18}H_{18}$
19	Benzo[b]chrysene	7.438	0.06	0.17	$C_{22}H_{14}$
20	3-Chloro-4,5-diaminobenzotrifluoride,	7.5	0.02	0.07	$C_{13}H_{12}ClF_3N_2O_3$
21	10-Hydroxyamitriptyline N-oxide	7.645	0.06	0.04	$C_{20}H_{23}NO_2$
22	**Palmitic acid**	7.865	5.03	8.82	$C_{16}H_{32}O_2$
23	Octahydroindeno[1,2,3,-cd]pyrene	8.032	0.36	0.53	$C_{22}H_{20}$
24	Plumbane, triethylmethyl-	8.38	0.03	0.06	$C_7H_{18}Pb$
25	1-Phenazinecarboxylic acid, 6-[1-[(1-	8.473	0.07	0.15	$C_{23}H_{26}N_2O_4$
26	3-tert-Butyl-5-chloro-1-(2,2-dichlorovinyl)-6-methyluracil	8.513	0.08	0.15	$C_{11}H_{13}Cl_3N_2O_2$
27	2,5-Ethano-2H-azocino[4,3-b]indole, 4-ethylidene-1,3,4,5,6,7-hexahydro-6-methylene-,	8.882	10.57	7.65	$C_{16}H_{32}O_2$
28	2H-1,5-Benzodiazepin-2-one,	9.14	0.27	0.29	$C_{11}H_8BrF_3N_2O_2$
29	cyclopentylidenephenylmethyl	9.365	0.79	1.41	$C_{18}H_{18}$

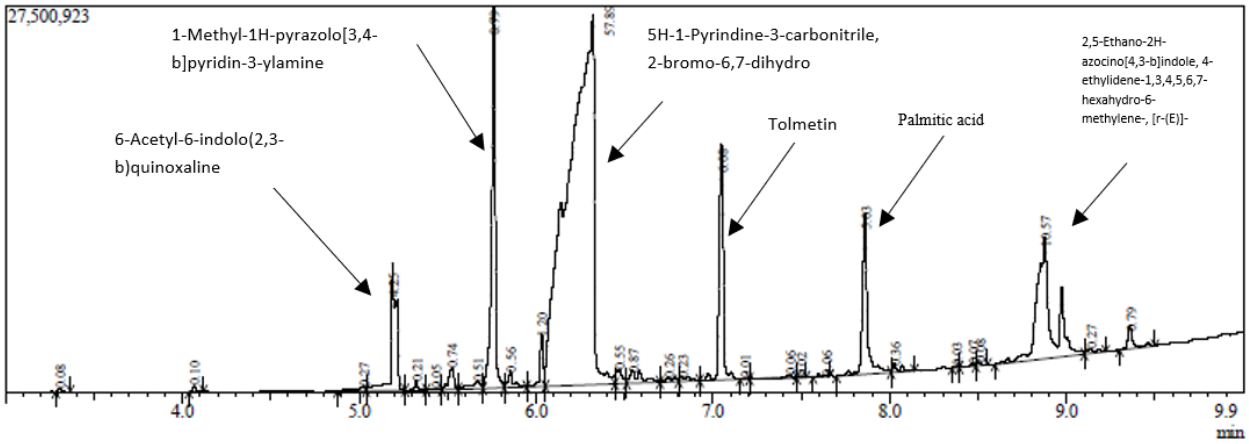

Fig 4. GC-MS analysis of cinnamon oil showing identified compounds.

Comparative examination of the compositional profile of cinnamon oil revealed that among its high concentration compounds, palmitic acid. Previous studies have reported the presence of palmitic acid in cinnamon bark oil. For instance, Rahman et al. (2022) have isolated 16.24% palmitic acid from cinnamon bark oil and 10.30% from cinnamon seed oil. It has been extensively reported in the scientific literature to demonstrate significant antimicrobial activity of palmitic acid. While cinnamon oil comprises several other compounds at high concentrations, exhaustive scrutiny of available research databases indicates the non-availability of peer reviewed research articles demonstrating the antimicrobial activity of these other major constituents. This finding suggests that palmitic acid will be the principal bioactive component responsible for the observed antimicrobial activity of cinnamon oil. For instance, Zhang et al. (2016) conducted extensive in vitro studies that validated the powerful antifungal properties of palmitic acid against Candida albicans and C. tropicalis. In a supporting study, Corbo et al. (2009) showing extensive growth inhibition against several economically relevant food spoilage fungi, including Aspergillus niger, Fusarium spp. and P. chrysogenum. These findings collectively

underscore the potential of palmitic acid as a pharmaceutical antifungal medication and as a natural food additive preservative, offering promising alternatives to conventional synthetic fungicides.

Palmitic acid is known for its significant antimicrobial activity through several well-documented mechanisms. The research by Santoso et al. (2022) describes how palmitic acid inserts into microbial cell membranes, where it causes structural destabilization that interferes with membrane permeability and, consequently, leads to cytoplasmic leakage. Complementary research by Zheng et al. (2005) determined that palmitic acid possesses inhibitory activity against central enzymes in microbial metabolic processes. Besides, Prasath et al. (2020) documented the efficacy of palmitic acid in effectively inhibiting biofilm formation by the pathogenic yeast Candida tropicalis. Similarly, Yosief and Sarker (2021) established that palmitic acid is a potent inhibitor of biofilm formation in S. aureus and other gram-positive bacterial pathogens, suggesting its application as a broad-spectrum antimicrobial agent. Also, Pyrazolo[3,4-b]pyridine showed to possess antimicrobial activity against (Bacillus subtilis, Staphylococcus aureus, Streptococcus pneumoniae, Escherichia coli, Salmonella Typhimurium, Aspergillus niger, and Fusarium oxysporum) (Salem and Ali, 2016). The results suggest that palmitic acid and 1-Methyl-1H-pyrazolo[3,4-b]pyridin-3-ylamine are novel potential antimicrobial agent

3.4. Shelf-Life Evaluation and Disease Reduction

Table 2 presents percent disease reduction in various treatments. The findings reflect that Cinnamon oil treatments exerted a significant effect in mitigating fungal infection in artificially injured and uninjured fruits. The uninoculated fruits remained untreated and had rapid disease progression, while cinnamon oil-treated fruits had significant protection towards *P. digitatum.* Fruits inoculated and cinnamon oil treated remained free from apparent infection caused by fungi for up to 22 days, and had a disease inhibition of 100% until day 16, though at day 22 this had fallen to 40% when fruits un-wounded. Inoculated fruits without cinnamon oil treatments had early infection by green mold, and total infection in later stages. Fruits wounded and inoculated and cinnamon oil treated had a disease inhibition at day 6 and fallen to 40% at day 12 then inhibition had fallen to 0% at day 22. Untreated and uninoculated controls had no infection initially but had attained 60% spontaneous infection at day 12 and had attained total infection at day 22. On the other hand, untreated inoculated fruits had attained total infection (100%) at the end of the experiment. Fruits inoculated and later treated with fungicide had total inhibition of infection after two days and had still had 80% inhibition at day 12, though at day 22 fruits had attained total infection. Statistical analysis confirmed that cinnamon oil application had a highly significant ($p < 0.01$) effect in minimizing disease occurrence compared to untreated controls, validating its antifungal efficacy for preservation in post-harvesting fruits of citruses.

Table 2: Percentage of green mold disease reduction on orange fruits for different treatments

Treatments	Un-Wounded					Wounded				
	2nd	6th	12th	16th	22nd	2nd	6th	12th	16th	22nd
T1	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	80 ± 0.44ab	80 ± 0.44ab	60 ± 0.54bc
T2	100 ± 0 a	100 ±0 a	0±0 e	0±0 e	0±0 e	100±0 a	60±0.54 bc	0±0 e	0±0 e	0±0 e
T3	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	0 ± 0a	100 ± 0 a	0±0 e	0±0 e	0±0 e	0±0 e

T4	100± 0a	100± 0a	100± 0a	100± 0a	60±0. 54bc	100±0 a	100±0 a	60±0. 54 bc	40±0. 54 cd	20 ± 0.44 d
T5	100 ± 0a	100 ± 0a	100 ± 0a	100 ± 0a	40 ± 0.54 cd	100 ± 0a	100 ± 0 a	40 0.44 cd	20 ± 0.44 d	0±0 e

T1: Control (Untreated and uninoculated); T2: Inoculated with *P. digitatum* and Untreated; T3: Inoculated with *P. digitatum* and treated with Fungicide; T4: Treated with cinnamon oil and uninoculated; T5: Treated with cinnamon oil and inoculated with *P. digitatum*

Citrus fruits treated with cinnamon oil showed significantly higher extended life as compared to the untreated controls. Application of cinnamon oil was adequate to protect fresh citrus fruits without visible mycelia development of fungi until 22 days. Green mold did not grow either in the untreated-wounded or treated-unwounded areas of both treated and nontreated but subsequently wounded or un wounded fruits following cinnamon oil application (Fig 5).

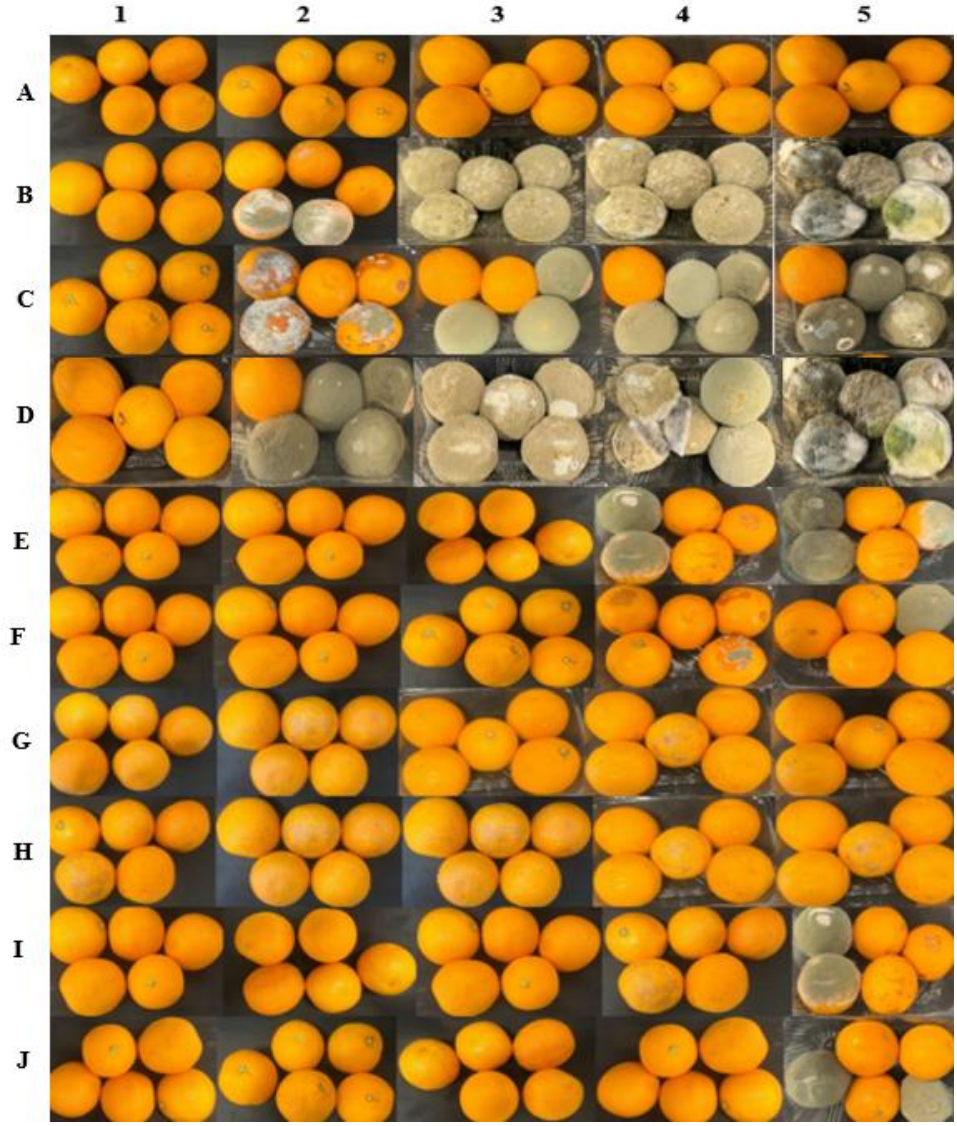

Fig 5. Reductions of *P. digitatum* populations on orange fruits by cinnamon oil compared with fungicide and untreated fruits from 2nd days to 22 days of treatment.

A: Control (Untreated and uninoculated (unwounded)); **B:** Control Untreated and

uninoculated (wounded); **C:** Control (Untreated and inoculated (unwounded)); **D:** Control Untreated and inoculated (wounded); **E:** Treated with fungicide and inoculated (wounded); **F:** Treated with fungicide and inoculated (unwounded); **G:** Treated with cinnamon oil and uninoculated (wounded); **H:** Treated with cinnamon oil and uninoculated (unwounded); **I:** Treated with cinnamon oil and inoculated (wounded); **J:** Treated with cinnamon oil and inoculated (unwounded); **1:** after 2 days; **2:** after 6 days; **3:** after 12 days ; **4:** after 16 days; **5:** after 22 days.

Orange fruits were weighed before and after treatment for 22 days to determine the efficacy in weight loss resulting from cinnamon oil. Fig 6 shows varied treatments and percentages for weight loss. Fruits inoculated or uninoculated and cinnamon oil treated had no loss in weight and remained in good quality and freshness for the whole duration of the experiment.

For comparison, uninoculated and untreated fruits inoculated with *P. digitatum* had highest loss in weight, at 60% in injured fruits and 45% in uninjured fruits. Alternatively, untreated but uninoculated fruits had loss at 53% in injured fruits and at 18% in uninjured fruits and reflect moisture loss resulting from nature as another cause for loss after harvest. Fruit inoculated with *P. digitatum* and treated with fungicide had mild weight loss at 55% in injured and at 40% in uninjured fruits. These findings confirm that cinnamon oil-treated fruits retained their quality and exhibited no measurable weight loss over the 22-day storage period. The results support its potential as a natural preservative for post-harvest citrus fruit management.

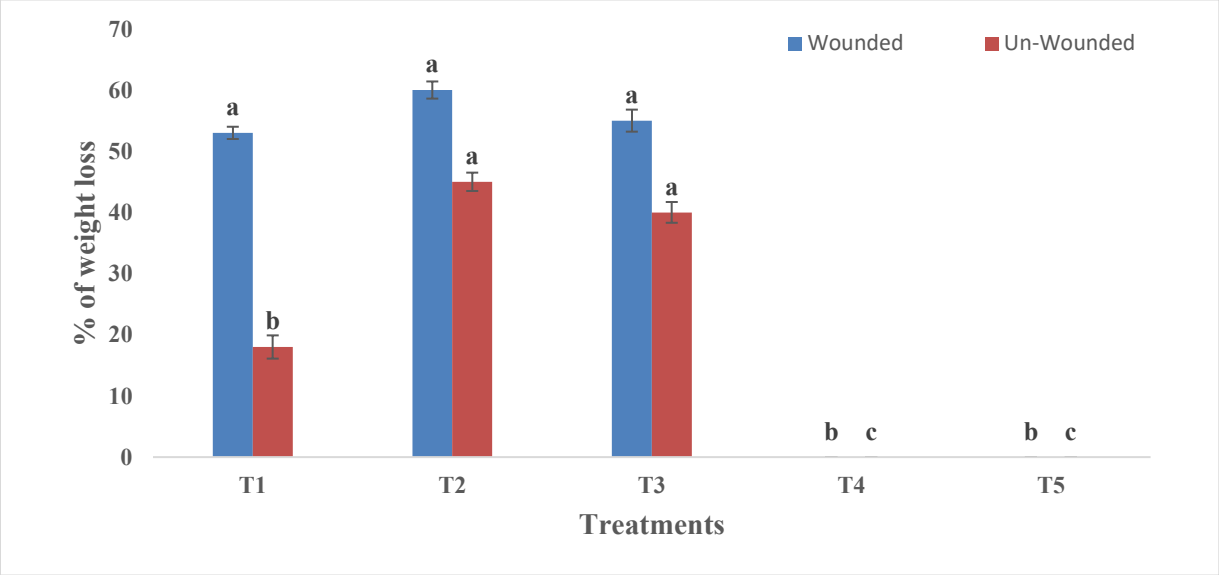

Fig 6. Percentage of orange weight loss by *P. digitatum* compared with cinnamon oil treatment

T1: Control (Untreated and uninoculated); T2: Inoculated with *P. digitatum* and Untreated; T3: Inoculated with *P. digitatum* and treated with Fungicide; T4: Treated with cinnamon oil and uninoculated; T5: Treated with cinnamon oil and inoculated with *P. digitatum.*

Such mechanisms are in accord with plant-based bioactive substances' general antimicrobial activity, as recorded by Kaseke et al. (2023). The biological efficacy of cinnamon oil as an antifungal agent renders it a viable candidate for application in managing post-harvest disease as a chemical fungicide alternative. Findings in this research are congruent with previous research in support of utilization of essential oils as sustainable alternative chemical-based fungicides based on low toxicity, biodegradation, and extensive spectrum antimicrobial activity (Sun et al., 2022).

Some research has demonstrated the potential of plant extracts and essential oils as postharvest treatments to extend the shelf life of fruits

through their antimicrobial activities. Such natural treatments have the potential to provide alternatives to conventional synthetic fungicides due to their lower environmental burden and consumer safety profile. For instance, comparative studies on various medicinal plant essential oils by Azizi et al. (2010) established a clear hierarchy of inhibitory activity against *P. italicum*. Their results demonstrated total radial growth inhibition at various concentrations: Thymus vulgaris (500 mg/L), and *Satureja hortensis* and *Trachyspermum copticum* (1000 mg/L). The researchers established an efficacy gradient of *T. vulgaris* > *T. copticum* > *S. hortensis* > *Cuminum cyminum* > *Mentha piperita*, where inhibitory activity is directly related to concentration levels. Singh and Sumbali (2007) compared various leaf extracts as pre-infection treatment, and *Adiantum capillus* venaris extract was found most effective, followed by *Thuja occidentalis* and *Eucalyptus globulus* extracts, which were statistically equal in activities. In addition, Mentha and Ocimum species essential oils inhibited considerable development of postharvest rot.

Furthermore, Permadi et al. (2024) demonstrated that citrus-derived essential oils exhibited very high inhibitory activity against *P. digitatum*, pointing toward potential applications of these oils in the integrated pest management of citrus fruits. Daniel et al. (2015) evaluated the antifungal activity of garlic extracts and clove oil against various postharvest pathogens (*Botrytis cinerea*, *Penicillium expansum*, and *Neofabraea alba*) on various apple varieties. Their experimental design was particularly noteworthy in determining direct application and volatile exposure modes, and both treatment modes had considerable reduction in decay incidence relative to untreated controls. Givi et al. (2019) also conducted extensive preventive treatments by immersing damaged fruits in various concentrations of pomegranate peel extract and essential oil before intentional inoculation with 20 µL of *P. italicum* or *P. digitatum* suspensions. The findings revealed outstanding protective effects, with pomegranate derivatives reducing infected wound percentage and lesion diameter by 75% and 100%, respectively, reflecting complete inhibition at optimal concentrations. In a simultaneous study, Fadda et al. (2021) examined myrtle leaf extract against various Penicillium species (*P. digitatum, P. italicum*, and *P. expansum*) on mandarins inoculated artificially and stored for 12 days at 20°C and 90% relative humidity. All the extracts were found to be completely inhibited from fungal growth at 20 g L^{-1} concentrations, demonstrating the broad-spectrum antifungal property of this plant source.

Conclusion

In this study, cinnamon oil showed intense inhibition against Penicillium digitatum, GC-MS analysis of which identified palmitic acid and 1-Methyl-1H-pyrazolo[3,4-b]pyridin-3-ylamine to be the major bioactive molecules behind this antifungal activity. Besides, cinnamon oil treatment further enhanced fruit quality traits and extended citrus postharvest shelf life by suppressing fungal infection and prolonging the shelf life for up to 22 days. In addition to the nutritional and sensory evaluation of the cinnamon application on the stored citrus fruits, large-scale field applications, commercial condition storage trials that simulate true postharvest environments, and wider efficacy testing against a broad spectrum of economically significant plant pathogens should be part of future research activities.

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