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Antifungal Activity of *Gliocladium viride* against *Fusarium oxysporum*

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ABSTRACT

***Fusarium oxysporum* is a cosmopolitan fungal species that can cause wilt disease in various plants. This study aimed to determine the antifungal activity of *Gliocladium viride* against *F. oxysporum* and identify the antifungal compound produced by *G. viride*. An antagonistic test of *G. viride* against *F. oxysporum* was carried out in dual culture. The antifungal activity of *G. viride* extract on the growth of *F. oxysporum* was determined using the paper disc diffusion method. The results showed that *G. viride* inhibited the growth of *F. oxysporum* colonies, with inhibition percentages ranging from 92.93% to 93.92%. The extract has antifungal activity, with the diameter of the inhibition zone formed being categorized as strong inhibition, which ranges from 19.3 mm to 24.5 mm. *G. viride* extract contains eleven compounds that have antifungal activity, namely cyclopropanecarboxylic acid; 2-nonanone; 2,3-butanediol; 2-heptanone; acetoin; 2,3-dimethylpyrazine; carbamic acid, phenyl esters; pyridine, 2,3,4,5-tetrahydro; 2-furancarboxaldehyde, 5-methyl; caryophyllene; and 1,2, benzenedicarboxylic acid. The results of this study provide information that *G. viride* can be used as a biological agent to control wilt in banana, vanilla, tomato and chili plants.**

Keywords: *Gliocladium viride*, antifungal activity, *Fusarium oxysporum*

INTRODUCTION

Fusarium oxysporum fungus is a soil-borne pathogen that has more than 100 formae speciales (f.sp.) that have been known to cause disease in different hosts (Baayen *et al.* 2000). Some of the formae speciales *of F. oxysporum* are *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici,* and *F. oxysporum fsp. capsici*. The fungus *F. oxysporum fsp. cubense* is a pathogen in banana plants. Warman and Aitken (2018) reported that the cause of wilt disease in banana plants is *F. oxysporum fsp. cubense.* The fungus *F. oxysporum fsp. vanilla* is a pathogen in vanilla plants. Mosqueda *et al.* (2019) reported that the cause of wilt disease in *Vanilla planifolia* plants is *F. oxysporum f. sp. vanillae* wthat can cause stem and root rot. The fungus *F. oxysporum fsp. lycopersici* is a pathogen in tomato plants. Srinivas *et al.* (2019) reported that the cause of wilt disease in tomato plants (*Lycopersicon esculentum* Mill.) is *F. oxysporum fsp. lycopersici*. Meanwhile, the fungus *F. oxysporum fsp. capsici* is a pathogen in chili plants. Gabrekiristos and Demiyo (2020) reported that the cause of wilt disease in *Capsicum annum* L plants. is the fungus *F. oxysporum fsp. capsici.*

Currently, fusarium wilt disease control still uses synthetic fungicides. Song *et al.* (2003) reported that fungicides with active ingredients prochloraz, carbendazim, thiram, toclofos methyl, hymexazol, azoxystrobin, and carboxin are effective in controlling fusarium wilt disease. Nevertheless, the continuous use of synthetic fungicides can affect soil health. According to Roman *et al.* (2021), high doses of fungicides can affect the community of microorganisms in the soil, causing a decrease in the population of soil microorganisms. One of the efforts to reduce synthetic fungicides is to use the biological agent *Gliocladium viride*. One of the mechanisms of *G. viride* fungi in controlling pathogenic fungal populations is by producing antifungal compounds. As is the case with the fungus *Trichoderma asperellum* reported by Srinivasa *et al.* (2017), it can produce antifungal compounds viridin, viridiol, ferulic acid, gliovirin which have been proven to inhibit the growth of *Sclerotium rolfsii* fungus with an inhibitory percentage of 80.04%. Meanwhile, *T. harzianum* was reported by Siddiquee *et al.* (2012) can produce antifungal compounds 2,3-butanediol, 3-methyl-2,5-furandione, phenylethyl alcohol, carbamic acid, phenyl ester, and decahydro-1,6-dimethyl-naphthalene. The genus *Gliocladium* has been known as one of the fungi antagonists to *F. oxysporum*, but the antifungal compounds produced are not yet known. This study aims to test the antifungal activity *of G. viride* against the fungus *Fusarium oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici* and identify antifungal compounds produced by *the G. viride*.

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METHODS

Materials and Equipment

This research was carried out at the Plant Disease Science Laboratory, Faculty of Agriculture, Udayana University, and the Bali Police Forensic Laboratory from April to June 2023. The materials used were the fungus *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici,* biological agent *G. viride*, and potato dextrose agar (PDA) media. The instruments included test tubes, micropipettes, digital scales, Ose needles, microscopes, laminar flow cabinets, and gas chromatography-mass spectrometry (GCMS).

In vitro Antagonistic Test *of G. viride* against F. oxysporum Fungus

The antagonistic test *of G. viride* against the fungi *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici in vitro* was carried out based on Khalimi and Wirya (2009) procedure. The test of G*. viride antifungal activity* against the growth of fungi *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici* began by preparing the growth medium by pouring 10 mL of PDA media on a petri dish. Furthermore, the mushrooms *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici* were inoculated in the center of a petri dish that already contained PDA media, then *G. viride* was inoculated in 4 positions, flanking *the fungus Fusarium* spp. with 2 cm distance. The design used in this study was a Complete Randomized Design (RAL) with 8 treatments and 4 replicates.

The determination of the percentage of inhibition of biological bacteria to fungal growth was determined by the following formula:

$$\text{Inhibition} = \frac{\text{Control colony area} - \text{Treatment colony area}}{\text{Control colony area}} \times 100\%$$

The growth rate of a fungus colony was determined using the following formula:

$$\text{Colony growth rate} = \frac{\text{Control colony area at last observation}}{\text{Time lapse}}$$

Antifungal Activity Test of *G. viride* Extract against F*. oxysporum in vitro*

G. viride extract was produced from dual cultures of *G. viride* and *F. oxysporum. F. oxysporum* colonies were removed first, followed by *G. viride* cultures dissolved in methanol at a ratio of 10 *G. viride* culture cultures per 100 mL of methanol in petri dishes. Furthermore, it was macerated for 48 hours before being extracted with a vacuum rotary evaporator (Model HEA-02. The disc paper diffusion method was used to test the antifungal activity of *G. viride* extract against fungus *F. oxysporum fsp spp. cubense, F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici*, and F. *oxysporum fsp. capsici*. The test started with preparing the growth medium by putting 1 mL of each *F. oxysporum* suspension into a petri dish. Next, 10 mL of PDA medium was added to a petri dish, then inoculated the solidified medium with a 6 mm diameter disc paper that had previously been soaked in *G. viride* extract. Inhibition zones were defined as areas that did not appear to be overgrown with fungus. Tendencia (2004) classified inhibition zones in disk diffusion tests into three categories: (1) weak inhibition, less than 14 mm, (2) medium inhibition, 15–18 mm, and (3) strong inhbition > 18 mm.

Identification of Antifungal Compounds from G. *viride* Extract

Antifungal compounds of *G. viride* extract were evaluated by GCMS (7890A GC-system 5975C inert XL E1/C1 MSD model G3174A, Agilent Technologies, Wilmington, DE, USA) using Ahamed and Ahring's (2011) approach. A sample of 2 µL extract was put into the GCMS. The injector temperature was held at 240°C for 26 min. Antifungal compounds were identified using a comparison of the 2023 NIST database library, and the chemical names used in this research were consistent with the NIST database nomenclature.

RESULTS AND DISCUSSION

In vitro Antagonistic Test *of G. viride* against F. oxysporum

The results of the G. viride *antagonistic test* against *F. oxysporum* in vitro showed that *G. viride* inhibited the growth of fungal colonies *of F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici,* with the % inhibition ranging from 92.93% to 93.92% (Table 1).

The fungal colonies *of F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici* in the control treatment grew normally, with the colony growth rate ranging from 802.62 mm^2/day to 890.20 mm^2/day (Figure 1). Meanwhile, fungal colonies in *G. viride* treatment were inhibited in growth. It can be seen in the fungus colony area's low value, which manifests fungal growth. The lower the value of the area of the fungal colony, the higher the value of the inhibition of biological bacteria to the fungus. Fungal growth in *G. viride* treatment *wa*s inhibited due to the presence of antifungal compounds produced by *G. viride* through the antibiotic mechanism. The growth of fungi in *G. viride* treatment was inhibited, with colony growth rates ranging from 50.86 mm^2/day to 59.69 mm^2/day. Demirci *et al.* (2011) showed that *G. viride* ME-7 can inhibit the growth of *Rhizoctonia solani* fungus with an inhibitory percentage of 35%. Meanwhile, Agustina *et al.* (2019) reported that *Gliocladium* sp. inhibits the

Table 1 Results of the G*. viride* antagonistic test against fungi *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanilae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici* secara *in vitro*

Treatment	Area of fungal colonies (mm^2)	Colony growth rate (mm^2/day)	Inhibition (%)
F. oxysporum fsp. cubense	4013.11 a*	802.62 a	-
G. viride **+** *F. oxysporum fsp. cubense*	283.38 b	56.67 b	92.93
F. oxysporum fsp. vanilae	4183.26 a	836.65 a	-
G. viride **+** *F. oxysporum fsp. vanilae*	254.34 b	50.86 b	93.92
F. oxysporum fsp. lycopersici	4415.62 a	883.12 a	
G. viride **+** *F. oxysporum fsp. lycopersici*	268.66 b	53.73 b	93.91
F. oxysporum fsp. capsici	4451.02 a	890.20 a	
G. viride **+** *F. oxysporum fsp. capsici*	298.49 b	59.69 b	93.29

Remaks:*Values in the same column followed by the same letter do not differ significantly (p>0.05) according to the Duncan Multiple Distance Test at the 5% level.

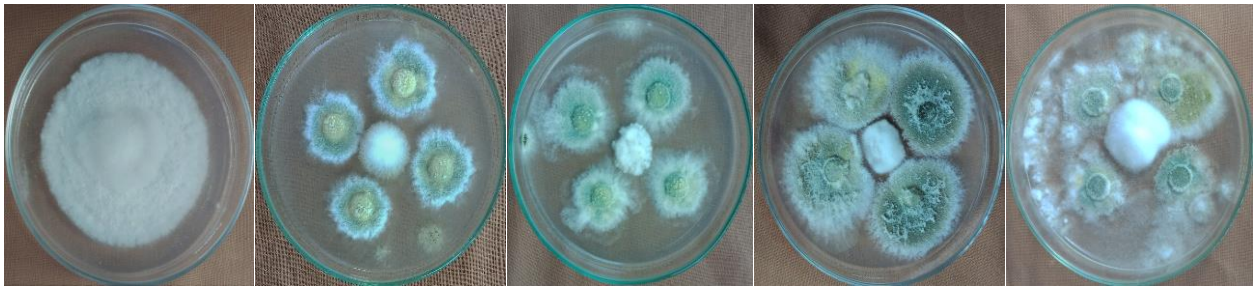


Figure 1 Results of G*. viride* antagonistic test against *Fusarium* spp. fungus *in vitro*. A: Control *F. oxysporum fsp. vanilae*, B: *G. viride* **+** *F. oxysporum fsp. cubense*, C: *G. viride* **+** *F. oxysporum fsp. vanilae*, D: *G. viride* **+** *F. oxysporum fsp. lycopersici,* E: *G. viride* **+** *F. oxysporum fsp. capsici.*

growth of *Botryodiplodia theobrome* fungus with an inhibition percentage of 84.56% in *in vitro* testing.

Antifungal Activity Test of *G. viride* Extract against *F. oxysporum*

The results of the antifungal activity test of *G. viride extract* against the fungus *F. oxysporum in vitro* showed that *the* extract had antifungal activity against the fungus *F. oxysporum fsp. cubense*, *F. oxysporum fsp. vanillae, F. oxysporum fsp. lycopersici, F. oxysporum fsp. capsici,* with the inhibition zone's diameter, is categorized as strong resistance and ranges from 19.3 mm to 24.5 mm. The extract *extract* was able to inhibit the fungus *F. oxysporum fsp. cubense* with an inhibitory zone diameter of 19.3 mm, while the diameter of the inhibitory zone on *F. oxysporum fsp. capsici, F. oxysporum fsp. lycopersici,* and *F. oxysporum fsp. vanilla* were 19.8 mm, 20.2 mm, and 24.5 mm, respectively. The extract has antifungal activity, indicated by forming an inhibition zone around the disc paper (Figure 2). The inhibition zone is caused by the presence of antifungal compounds produced by the fungus *G. viride*. According to Ahamed and Ahring (2011), the identification of chemical compounds in *Gliocladium* sp. 62724 extract using GC-MS-SPME shows that the extract contains benzene, heptane, 1-octene, octane, *m*-xylene, 3-methylnonane, dodecane, tridecane, hexadecane, and nonadecane.

Identification of Antifungal Compounds from G*. viride Extract*

Based on the results of the GCMS analysis, *G. viride* extract contained 19 compounds. They are 2-hexanone; cyclopentanol, 3-methyl; propanal, 2,3-dihydroxy; propanoic acid, 2-hydroxy ethyl ester; propanoic acid, 2-hydroxy ethyl ester; 4-nitro-3-oxobutyric acid, methyl ester; benzene, 1,4-dimethyl; cyclopropanecarboxylic acid; cyclopropanecarboxylic acid; 2-nonanone; 2,3-butanediol; 2-heptanone; acetoin; 2,3-dimethylpyrazine; carbamic acid, phenyl ester; pyridine, 2,3,4,5-tetrahydro; pyridine, 2,3,4,5-tetrahydro; 2-furancarboxaldehyde, 5-methyl; caryophyllene; dan 1,2, benzenedicarboxylic acid (Table 2).

According to GCMS analysis, *G. viride* extract contains 11 compounds, including cyclopropanecarboxylic acid, 2-nonanone, 2,3-butanediol, 2-heptanone, acetoin, 2,3-dimethylpyrazine, carbamic acid, phenyl ester, pyridine, 2,3,4,5-tetrahydro, 2-furancarboxaldehyde, 5-methyl, caryophyllene, and 1,2-benzenedicarboxylic acid. Cyclopropanecarboxylic acid molecules were found at peaks 7 and 8, with retention time of 3.361 min and 3.552 min, respectively, and area of 5.98% and 5.69%. The 2-nonanone was discovered at peak 9, with a retention time of 3.596 min and an area of 11.16%. The molecule 2,3-butanediol was identified at peak 10

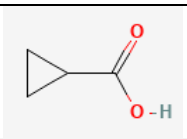
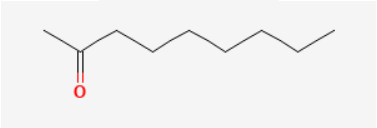
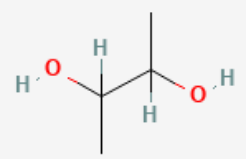
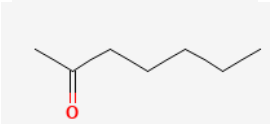
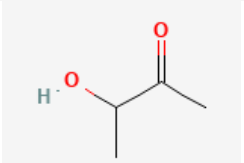
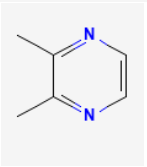
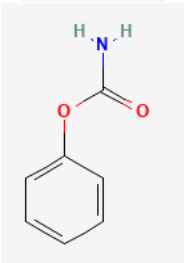
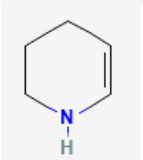
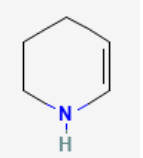
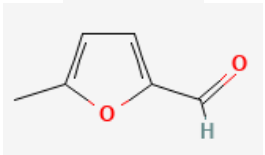
Figure 2 Results of antifungal activity test of *G. viride* extract against *F. oxysporum.* A: *F. oxysporum fsp. cubense*, B: *F. oxysporum fsp. vanilae*, C: *F. oxysporum fsp. lycopersici,* D: *F. oxysporum fsp. capsici.*

Table 2 Results of GC-MS analysis of chemical compounds in *G. viride extract*

Peak	Retention time	Area (%)	Chemical compounds identified	Chemical formula	Chemical structure*
1	2.122	1.18	2-hexanone	$C_4H_9COCH_3$	
2	2.168	1.46	3-methyl cyclopentanol	$C_6H_{12}O$	
3	2.189	1.64	2,3-dihydroxy propanal	$C_3H_6O_3$	
4	2.585	1.07	propanoic acid, 2-hydroxy ethyl ester 2-ethylhexyl (2*S*)-2-hydroxypropanoate	$C_5H_{10}O_3$	
5	2.651	1.11	4-nitro-3-oxobutyric acid, methyl ester	$C_{11}H_{11}NO_5$	
6	3.313	2.98	1,4-dimethyl benzene	C_8H_{10}	
7	3.361	5.98	cyclopropanecarboxylic acid	$C_4H_6O_2$	

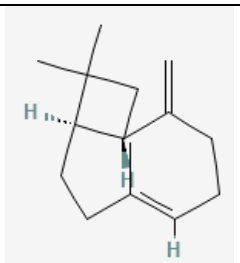
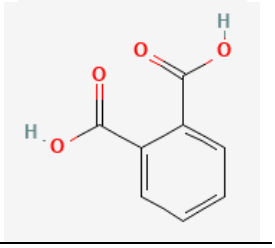
with a retention time of 3.842 min and an area of 2.30%.

Tabel 2 Results of GC-MS analysis of chemical compounds in *G. viride extract* (advanced)

Peak	Retention time	Area (%)	Chemical compounds identified	Chemical formula	Chemical structure*
8	3.552	5.69	cyclopropanecarboxylic acid	$C_4H_6O_2$	
9	3.596	11.16	2-nonanone	$C_9H_{18}O$	
10	3.842	2.30	2,3-butanediol	$C_4H_{10}O_2$	
11	3.879	4.70	2-heptanone	$C_7H_{14}O$	
12	3.976	2.16	acetoin	$C_4H_8O_2$	
13	4.013	5.95	2,3-dimethylpyrazine	$C_6H_8N_2$	
14	4.183	13.75	carbamic acid, phenyl ester	$C_7H_7NO_2$	
15	4.218	26.35	2,3,4,5-tetrahydro pyridine 1,2,3,4-tetrahydro pyridine	C_5H_9N	
16	4.596	3.64	2,3,4,5-tetrahydro pyridine	C_5H_9N	
17	4.632	1.45	5-methyl 2-furancarboxaldehyde	$C_6H_6O_2$	

The 2-heptanone was discovered at peak 11 with a

Tabel 2 Results of GC-MS analysis of chemical compounds in *G. viride extract* (advanced)

Peak	Retention time	Area (%)	Chemical compounds identified	Chemical formula	Chemical structure*
18	24.699	5.24	caryophyllene	$C_{15}H_{24}$	
19	24.998	2.19	1,2-benzenedicarboxylic acid	C_8H_6O	

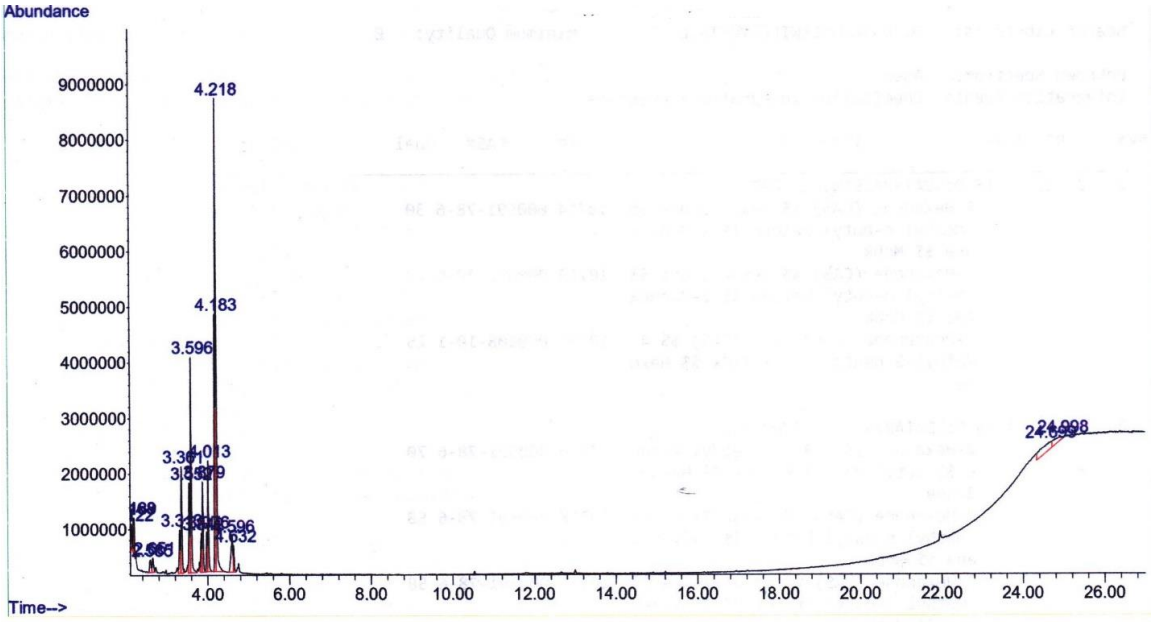


Figure 3 GC-MS chromatographic representative data from *G. viride* extract.

with a retention time of 3.842 min and an area of 2.30%.

The 2-heptanone was discovered at peak 11 with a retention time of 3.879 min and an area of 4.70%. Acetoin was found at peak 12 at 3.976 min, having an area proportion of 2.16%. The 2,3-dimethylpyrazine was identified at peak 13 with a retention time of 4.013 min and an area of 5.95%. The carbamic acid compound phenyl ester was discovered at peak 14 with a retention time of 4.183 min and an area of 13.75%. The pyridine 2,3,4,5-tetrahydro was discovered at peaks 15 and 16 with retention time of 4.218 and 4.596 min, respectively, and area of 26.35% and 3.64%. The 2-furancarboxaldehyde was identified at peak 17 with a retention time of 4.632 min and an area of 1.45%. The 5-methyl-caryophyllene was discovered at peak 18 with a retention time of 24.699 min and an area of 5.24%. Compound 1,2-benzenedicarboxylic acid was discovered at peak 19 with a retention time of 24.998 min and an area of 2.19% (Figure 3).

Several compounds, including cyclopropanecarboxylic acid, 2-nonanone, 2,3-butanediol, 2-heptanone, acetoin, 2,3-dimethylpyrazine, carbamic acid, phenyl ester, pyridine, 2,3,4,5-tetrahydro, 2-furancarboxaldehyde, 5-methyl caryophyllene, and 1,2-benzenedicarboxylic acid, have been shown to have antifungal properties. Guaranda *et al*. (2023) discovered that *Trichoderma reesei* extract (C2A) contains cyclopropanecarboxylic

acid with antifungal activity against *Moniliophthora perniciosa* and *M. roreri.* According to Calvo et al. (2020), *Bacillus velezensis* strains BUZ-14 extract contains 2-nonanone, 2,3-butanediol, 2-heptanone, acetoin, and 2,3-dimethylpyrazine, which have antifungal activity against *Botrytis cinerea*, *Monilinia fructicola*, *M. laxa*, *Penicillium italicum*, *P. digitatum*, and *P. expansum*. According to Yaseri *et al*. (2016), *Proteus mirabilis* extract contains 2-furancarboxaldehyde, which has antifungal action against *Aspergillus terreus*, *A. flavus*, *Candida albicans*, *Microsporum canis*, and *Trichophyton mentagrophytes*. Tabarestani *et al*. (2016) found that *Trichoderma virens* extract includes caryophyllene that show antifungal action against *F. oxysporum*. Siddiquee *et al*. (2012) discovered that *T. harzianum* strain FA1132 extract contains 2,3-butanediol, carbamic acid phenyl ester, and 1,2, benzenedicarboxylic acid, which have antifungal action against *Fusarium graminearum*, *Rhizoctonia solani*, and *F. oxysporum* f.sp. lycopersici. Dai *et al*. (2011) discovered that 6-alkyl-2,3,4,5-tetrahydropyridine exhibits antifungal properties against *Cryptococcus neoformans*, *Candida albicans*, *C. glabrata*, and *C. krusei*. According to Li *et al*. (2021), *Streptomyces* sp. H4 includes 1,2, benzenedicarboxylic acid, which shows antifungal activity against *Colletotrichum fragariae*.

G. viride produces eleven antifungal chemicals that work together to suppress the growth of harmful fungus. Compounds in the group of fatty acids such as cyclopropanecarboxylic acid, carbamic acid phenyl ester, and 1,2, benzenedicarboxylic acid work simultaneously in inhibiting fungal growth by interfering with cell membrane permiability, especially in cells with low sterol content, inhibiting the action of the topoisomerase enzyme, which plays an important role in the DNA replication process in the nucleus and the translation process in ribosomes, inhibiting the formation of N-myristoyltransferase, which plays an important role in the translation process in ribosomes, inhibits β-oxidation in mitochondria, inhibits the formation of triacylglycerol and sphingolipids in mitochondria, causing mitochondrial damage (Pohl *et al.* 2011).

The mechanism of 2-nonanone, 2,3-butanediol, 2-heptanone, acetoin, 2,3-dimethylpyrazine, pyridine 2,3,4,5-tetrahydro, 2-furancarboxaldehyde 5-methyl, and caryophyllene in inhibiting fungal growth is thought to be by inducing apoptosis, causing DNA and mitochondrial damage (Prasath *et al.* 2020), inhibiting the action of nitric oxide dioxygenase (Helmick *et al.* 2005), inhibits ergosterol biosynthesis (Hori *et al.* 2000), inhibits the formation of fungal cell membranes by methylating sterols and sterol esters (Ozdemir *et al.* 2010), inhibiting the formation of fungal cell walls by inhibiting the synthesis of β-glucan and chitin (Chudzik *et al.* 2019), and causes cell death by inhibiting the action of enzymes that play a role in DNA and RNA synthesis in fungal cells (Pippi *et al.* 2017).

CONCLUSION

The results of this investigation show that *G. viride* fungus can limit the growth of *F. oxysporum* fungal colonies with inhibition ranging from 92.93% to 93.92%. *G. viride* extract possesses antifungal activity, with an inhibition zone diameter ranging from 19.3 mm to 24.5 mm, indicating significant inhibition. GC-MS analysis identified 11 antifungal compounds in the extract, including cyclopropanecarboxylic acid, 2-nonanone, 2,3-butanediol, 2-heptanone, acetoin, 2,3-dimethylpyrazine, carbamic acid, phenyl ester, pyridine, 2,3,4,5-tetrahydro, 2-furancarboxaldehyde, 5-methyl, caryophyllene, and 1,2-benzenedicarboxylic acid.

REFERENCES

Agustina D, Triasih U, Dwiastuti ME, Wicaksono R.C. 2019. Potensi jamur antagonis dalam menghambat pertumbuhan jamur *Botryodiplodia Theobromae* penyebab penyakit busuk batang pada tanaman jeruk. *Jurnal Agronida.* 5(1): 1–6. https://doi.org/10.30997/jag.v5i1.1852

Ahamed A, Ahring BK. 2011. Production of hydrocarbon compounds by endophytic fungi Gliocladium species grown on cellulose. *Bioresource Technology.* 102: 9718–9722. https://doi.org/10.1016/j.biortech.2011.07.073

Baayen RP, Donnell K, Bonants PJ, Cigelnik E, Kroon LPNM, Roebroeck JA, Waalwijk C. 2000. Gene genealogies and aflp analyses in the *Fusarium oxysporum* complex identify monophyletic and nonmonophyletic formae speciales causing wilt and rot disease. *Ecology and Population Biology.* 90(8): 891–900. https://doi.org/10.1094/PHYTO.2000.90.8.891

Calvo H, Mendiara I, Arias E, Gracia AP, Blanco D, Venturini ME. 2020. Antifungal activity of the volatile organic compounds produced by *Bacillus velezensis* strains against postharvest fungal pathogens. *Postharvest Biology and Technology.* 166(111208): 1–10. https://doi.org/10.1016/j.postharvbio.2020.111208

Chudzik B, Katarzyna B, Wojciech D, Daniel P, Andrzej N, Alina O, Bozena P, Mariusz G. 2019. Antifungal effects of a 1,3,4-thiadiazole derivative determined by cytochemical and vibrational spectroscopic studies. *Plos One.* 30: 1–32. https://doi.org/10.1371/journal.pone.0222775

Dai L, Jacob MR, Khan S, Khan IA, Clark AM, Li XC. 2011. Synthesis and Antifungal Activity of Natural Product-Based 6-Alkyl-2,3,4,5-tetrahydropyridines. *Journal of Natural Products.* 74: 2023–2026. https://doi.org/10.1021/np200644s

Demirci E, Dane E, Eken C. 2011. In vitro antagonistic activity of fungi isolated from sclerotia on potato tubers against *Rhizoctonia solani*. *Turkish Journal of Biology.* 35: 457–462. https://doi.org/10.3906/biy-1004-98

Gabrekiristos E, Demiyo T. 2020. Hot pepper fusarium wilt (*Fusarium oxysporum* f. sp. *capsici*): epidemics, characteristic features and management options. *Journal of Agricultural Science.* 12(10): 347–360. https://doi.org/10.5539/jas.v12n10p347

Guaranda IC, Lozano FE, Araujo DR, Romero C, Manzano P, Galarza L, Sosa D. 2023. Chemical characterization of *Trichoderma* spp. extracts with antifungal activity against cocoa pathogens. *Molecules.* 28(3208): 1–14. https://doi.org/10.3390/molecules28073208

Helmick RA, Arin EF, Anne MG, Christopher RG, Angela NH, Michael CG, Paul RG. 2005. Imidazole antibiotics inhibit the nitric oxide dioxygenase function of microbial flavohemoglobin. *Antimicrobial agents and chemotherapy.* 49(5): 1837–1843. https://doi.org/10.1128/AAC.49.5.1837-1843.2005

Hori K, Akira S, Michinari K, Koichi I, Yuri A, Yuso Y. 2000. Structure-activity relationships of a new antifungal imidazole, AFK-108, and related coumpounds. *Chem. Pharm. Bull.* 48(1): 60–64. https://doi.org/10.1248/cpb.48.60

Khalimi K, Wirya GNA. 2009. Pemanfaatan plant growth promoting rhizobakteria untuk biostimulan dan bioprotektan. *Ecotrophic.* 4(2): 131–135.

Li X, Jing T, Zhou D, Zhang M, Qi D, Zang X, Zhao Y, Li K, Tang W, Chen Y, Qi C, Wang W, Xie J. 2021. Biocontrol efficacy and possible mechanism of *Streptomyces* sp. H4 against postharvest anthracnose caused by *Colletotrichum fragariae* on strawberry fruit. *Postharvest Biology and Technology.* 175(111401): 1–11. https://doi.org/10.1016/j.postharvbio.2020.111401

Mosqueda MAR, Andreu LGI, Silva JAT, Rodriguez ML, Carrazana JCN, Aguilar JRB, Ovalle ORL, Gonzalez JM. 2019. In vitro selection of vanilla plants resistant to *Fusarium oxysporum f. sp. vanilla*. *Acta Physiologiae Plantarum.* 41(40): 1–8. https://doi.org/10.1007/s11738-019-2832-y

Ozdemir AO, Gulhan TZ, Zafer AK, Gokalp I, Shabana K, Fatih D. 2010. Synthesis and the selective antifungal activity of 5,6,7,8-tetrahydroimidazo[1,2-a]pyridine derivatives. *European Journal of Medicinal Chemistry.* 45: 2080–2084. https://doi.org/10.1016/j.ejmech.2009.12.023

Pohl CH, Kock JLF, Thibane VS. 2011. Antifungal free fatty acids: A Review. *Science Against Microbial Pathogens: Communicating Current Research and Technological Advances.* 60–71.

Pippi B, Paula R, Gabriella RMM, Vanessa ZB, Daiane FDL, Mario LT, Lucas LF, Ricardo JA, Saulo FA, Alexandre MF. 2017. Evaluation of 8-hydroxyquinoline derivatives as hits for antifungal drug design. *Medical Mycology.* 1–11.

Prasath KG, Tharani H, Mourya SK, Shunmugiah KP. 2020. Palmitic acid inhibits the virulence factors of candida tropicalis: biofilms, cell surface hydrophobicity, ergosterol biosynthesis, and enzymatic activity. *Frontiers in Microbiology.* 11(864): 1–21. https://doi.org/10.3389/fmicb.2020.00864

Roman DL, Voiculescu DI, Filip M, Ostafe V, Isvoran A. 2021. Effects of triazole fungicides on soil microbiota and on the activities of enzymes found in soil: A Review. *Agriculture.* 11(893): 1–18.

Song W, Zhou L, Yang,C, Cao X, Zhang L, Liu X. 2003.Tomato Fusarium wilt and its chemical control strategies in a hydroponic system. *Crop Protection.* 23: 243–247. https://doi.org/10.1016/j.cropro.2003.08.007

Siddiquee S, Cheong BE, Taslima K, Kausar H, Hasan MM. 2012. Separation and identification of volatile compounds from liquid cultures of *Trichoderma harzianum* by GC-MS using three different capillary columns. *Journal of Chromatographic Science.* 50: 358–367. https://doi.org/10.1093/chromsci/bms012

Srinivas C, Devi DN, Murthy KN, Mohan CD, Lakshmeesha TR, Singh B, Kalagatur NK, Niranjana SR, Hashem A, Alqarawi AA, Tabassum B, Abdallah EF, Nayaka SC, Srivastava RK. 2019. *Fusarium oxysporum f. sp. lycopersici* causal agent of vascular wilt disease of tomato: Biology to diversity– A review. *Saudi Journal of Biological Sciences.* 26: 1315–1324. https://doi.org/10.1016/j.sjbs.2019.06.002

Srinivasa N, Sriram S, Singh C, Shivashankar KS. 2017. Secondary metabolites approach to study the bio-efficacy of *Trichoderma asperellum* isolates in India. *Int. J. Curr. Microbiol. App. Sci.* 6(5): 1105–1123.

Tabarestani MS, Rahnama K, Jahanshahi M, Nasrollahnejad S, Fatemi MH. 2016. Identification of volatile organic compounds of *Trichoderma* spp. using static headspace gas chromatography-mass spectrometry. *Mycologia Iranica.* 3(1): 47–55.

Tendencia EA. 2004. Disk diffusion method. In Laboratory Manual of Standardized Methods for Antimicrobial Sensitivity Tests for Bacteria Isolated from Aquatic Animals and Environment. pp 13–29.

Warman NM, Aitken EAB. 2018.The movement of *Fusarium oxysporum f.sp. cubense* (sub-tropical Race 4) in susceptible cultivars of banana. *Frontier in Plant Science.* 9(1748): 1–9. https://doi.org/10.3389/fpls.2018.01748

Yaseri A, Kadhim WA, Hameed IH. 2016. Detection of volatile compounds emitted by *Proteus mirabilis* isolated from UTI patients and its anti-fungal potential. *Der Pharma Chemica.* 8(19): 671–678.