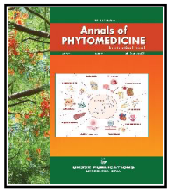
Annals of Phytomedicine 13(2): 979-986, 2024

DOI: http://dx.doi.org/10.54085/ap.2024.13.2.101

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Original Article : Open Access

Exploring fungal endophytes in a medicinal plant, *Lavandula officinalis* L.: Isolation, characterization, and plant growth-promoting potential

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Article Info

Article history
Received 1 October 2024
Revised 16 November 2024
Accepted 17 November 2024
Published Online 30 December 2024

Keywords
Lavandula officinalis L.
Endophytic fungi
Antifungal activity
Phytohormones

Abstract

This study focuses on isolating and characterizing endophytic fungi from lavender (*Lavandula officinalis* L.) to assess their antifungal activity and plant growth-promoting properties, marking one of the first investigations of this kind in the country. Using standard microbiological techniques, nine endophytic fungi were isolated and screened for enzyme production. The results revealed protease and lipase activity in several isolates, with notable cellulolytic activity indicated by filter paper degradation. Of the isolates, four were selected for further analysis. Isolate LR3 showed the highest levels of endo-1,4-β-glucanase and exo-1,4-β-glucanase activity, producing enzyme levels 4.22 times higher than the control. Isolate LS2 followed with enzyme activities of 3.72 and 2.63 units/ml, respectively, while LR2 also exhibited some endo-1,4-β-glucanase activity. The most active isolates, LS2 and LR3, were chosen for further study. When tested against pathogenic fungi, most endophytic isolates demonstrated activity against *Verticillium dahliae* and various Fusarium species, though they showed no activity against *Fusarium oxysporum*. Overall, this study highlights lavender-associated endophytic fungi as promising bioinoculants to support sustainable lavender cultivation.

1. Introduction

Medicinal plants have attracted substantial research interest due to their bioactive secondary metabolites, which offer promising medicinal applications. Among these, lavender (*Lavandula officinalis* L.), a member of the Lamiaceae family, holds notable economic value and is widely cultivated as an herb or shrub for use in the pharmaceutical and food industries (Hernandez-Leon *et al.,* 2021; Uritu *et al.,* 2018). Traditionally, lavender has been used to treat a variety of ailments, including wound healing, cardiovascular issues, colds, abdominal pain, and respiratory inflammation (Batiha *et al.,* 2023). Furthermore, phenolic compounds derived from the solid residue left after lavender essential oil distillation has exhibited antibacterial and antioxidant properties (Vasileva *et al.,* 2018). Endophytic fungi play an essential role in plant health and metabolism, producing bioactive compounds with significant biotechnological potential. These fungi not only support plants in natural conditions but are also valuable in controlled settings, such as micropropagation (Kanani *et al.,* 2020), bioremediation of organic pollutants and contaminants (Gupta *et al.,* 2020), and regulation of the plant's genetic response to biotic and abiotic stresses (Modi *et al.,* 2020). In this study, we characterize the endophytic fungi associated with *L. officinalis*. The bioactive properties of lavender indicate that its endophytic fungi may enhance plant protection against phytopathogenic fungi, potentially acting as plant growth-promoting rhizobacteria (PGPR) (Vârban *et al.,* 2022). However, despite lavender's medicinal significance, limited information is available on its endophytic fungi, particularly regarding their antifungal properties. Many medicinal plants in nature host endophytic fungi that produce metabolites capable of controlling and inhibiting phytopathogens responsible for plant diseases (Onsare *et al.,* 2013). There is an urgent need for natural agricultural strategies to replace the prolonged use of chemical fertilizers, aiming to enhance plant productivity, develop eco-friendly products, and reduce environmental pollution (Soliman *et al.,* 2020). Endophytic fungi, which reside within the internal or intercellular spaces of plant tissues without causing any disease symptoms, play multiple roles in promoting plant growth, including phytostimulation, biocontrol, and biofertilization (Eid *et al.,* 2019). These fungi directly support plant growth by fixing nitrogen, producing ammonia, solubilizing insoluble phosphates, and generating essential enzymes like cellulase, amylase, lipase, urease, and protease (Hassan, 2017; El-Esawi *et al.,* 2019; Kondrasheva *et al.,* 2022). Additionally, they protect plants from pathogenic microorganisms (Jabborova *et al.,* 2020).

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Research by Nthuku *et al.* (2023) identified endophytic fungi from lavender that showed strong activity against phytopathogenic fungi, with certain antagonistic isolates demonstrating notable endo-β-1,3-glucanase and exo-β-1,3-glucanase production. Although, *Ephedra* spp. has considerable medicinal significance, no studies have yet examined the plant growth-promoting potential of endophytic fungi from this genus. This study aims to expand the understanding of endophytic fungi associated with *L. officinalis* (lavender) and their role in enhancing plant growth and protection. Specifically, it focuses on isolating fungal endophytes from lavender and evaluating their plant growth-promoting properties. Key activities evaluated included enzymatic production (lipase, protease, and cellulase), antifungal effects against pathogenic fungi, inorganic phosphate solubilization, siderophore production, and the synthesis of phytohormones like indole acetic acid (IAA) and gibberellins.

2. Materials and Methods

2.1 Isolation of fungal endophytes

Lavender plants were collected from the Surkhandarya region in Uzbekistan (37.9409° N, 67.5709° E). Fungal endophytes were isolated from various plant parts, including roots, stems, and leaves. The samples were gathered within 1 h and initially rinsed under running water for 10-15 min to remove any attached rhizosphere and epiphytic bacteria, followed by air drying. Roots, stems, and leaves were each separated and weighed to one gram. The samples were then immersed in sterile distilled water, dried, and subjected to surface sterilization. For sterilization, stems and leaves were immersed in 70% ethanol for 1 min, followed by 4% sodium hypochlorite for 3 min, while roots were treated with 2% sodium hypochlorite for 10 min. Finally, samples were rinsed five times with sterile distilled water and thoroughly dried using sterilized filter paper. Next, root and stem samples were cut into small pieces and placed directly onto petri dishes, while leaves were crushed in a mortar and prepared by serial dilution up to 10^{-3}. One hundred microliters of each diluted leaf sample was spread onto petri dishes containing Czapek DOX, PDA, and Sabouraud nutrient media. Each sample was plated in triplicate. Plates were then incubated at 28 ± 2°C for 3-7 days to allow endophytic fungi to grow. Fungal colonies were then selected and transferred to three different nutrient media to obtain pure clones (Toppo *et al.,* 2024).

2.2 Phosphate solubilization

The isolated endophytic fungal strains were examined for their phosphate solubilization capabilities. The Pikovskaya nutrient medium was used, composed of the following (g/l): yeast extract (0.5), $Ca_3(PO_4)_2$ (5.0), $(NH_4)_2SO_4$ (0.5), KCl (0.2), $MgSO_4$ (0.1), $MnSO_4$ (0.0001), $FeSO_4$ (0.0001), and agar-agar (15), with a pH adjusted to 7. Additionally, 0.04% bromocresol purple was added as an indicator. The medium was poured into petri dishes, where pure fungal isolates were inoculated and incubated at 28 ± 2°C for one week. Each inoculation was performed in triplicate. In this case, phosphate-solubilizing enzymes produced by fungi capable of absorbing phosphorus alter the pH of the nutrient medium, leading to a color change in the medium and the formation of a halo or ring around the colony. The activity level of each fungal isolate is then determined based on the diameter of this ring (Mayadunna *et al.,* 2023).

2.3 Production of phytohormones by active isolates

2.3.1 Determination of gibberellic acid

Endophytic fungal strains were cultivated in liquid Czapek DOX medium at 28 ± 2°C on a shaker at 200 rpm for one passage. The amount of glucosamine (GK) was measured in the culture liquid of the micromycetes over a period of 7 days, beginning from the first day of cultivation, using the method described by Muromtsev and Nestyuk (Muromtsev *et al.,* 1960).To assess the GK content, 1.0 ml of the filtered culture liquid was transferred into 10 ml test tubes. Then, 1.0 ml of Folin-Chiocalto reagent, which consisted of 100 g Na_2O_4W, 25 g Na_2MoO_4, 700 ml of water, 50 ml of 85% H_3PO_4, 100 ml of concentrated HCl, 150 g $LiSO_4$, and 2-3 drops of bromothymol blue, was added to each tube, along with HCl. The mixture was then thoroughly mixed and left to react in the dark for 40 min. Samples containing GK exhibited a light to dark green coloration. The amount of GK in the samples was quantified using a spectrophotometer, measuring the optical density of the supernatants through a red light filter at a wavelength of 750 nm.

2.3.2 Determination of indole-3-acetic acid

Endophytic fungal strains were cultivated in their respective media at 28°C for 72 h. Once fully grown, the isolates were centrifuged at 3000 rpm for 30 min. Following centrifugation, 1.0 ml of the supernatant was transferred into 10 ml test tubes, to which 8.0 ml of Salkovsky's reagent-A mixture of 50 ml of 35% $\mathbf{H_2SO_4}$ and 0.5 ml of $\mathbf{FeCl_2}$ solution was added. The reaction mixture was thoroughly mixed and allowed to sit for 30 min. The samples turned red-pink, indicating the presence of indole-3-acetic acid (ISK). The amount of ISK in the samples was quantified using a spectrophotometer, measuring the optical density of the supernatants through a green light filter at a wavelength of 540 nm.

2.4 Siderophore production

The production of siderophores by the isolated endophytic fungi was evaluated using the method described by Schwyn and Neilands (1987). A solid nutrient medium containing chrome azurol S (CAS) was prepared and poured into petridishes. Discs measuring 4 mm from 1-week-old fungal mycelia were then inoculated onto the medium. The inoculated plates were incubated in the dark at 30°C for 5 to 7 days. Siderophore production was assessed by observing the formation of a distinct color change around the fungal discs in the blue medium. The diameter of the color zone was measured to quantify the extent of siderophore production.

2.5 Production of lipase

Endophytic fungi were cultivated in liquid nutrient medium at varying pH levels and temperatures for 7 days, followed by centrifugation at 3000 rpm for 10 min. The lipase activity in the resulting supernatant was quantified using the method described by Winkler and Stuckmann (1979), employing p-nitrophenyl palmitate (pNPP) as the substrate. To prepare the substrate solution, 1 ml of solution A, consisting of 10 ml of isopropanol containing 30 mg of pNPP, was mixed with 9 ml of solution B, which comprised 90 ml of 0.05 M phosphate buffer (pH 8.0) containing 207 mg of sodium deoxycholate and 100 mg of gum arabic. The substrate solution was heated to 37°C. Subsequently, 1 ml of the fungal extract was added to 2 ml of the prepared substrate solution in a 15-20 ml test tube. After incubating the mixture in a water bath at 37°C for 15 min, the optical density

was measured using a spectrophotometer at a wavelength of 410 nm. One unit (U) of enzyme activity was defined as the amount of enzyme required to release 1.0 mM of p-nitrophenol per minute. A standard curve was constructed using p-nitrophenol for reference.

2.6 Protease production

To qualitatively assess the protease activity of endophytic fungi, a sterilized skimmed milk agar medium was prepared with the following composition (g/l): pancreatic digest of casein-5.0, yeast extract-2.5, glucose-1.0, agar-15.0, distilled water-1000 ml, and 7% skim milk (used as an inducer). The fungal isolates were inoculated into the medium and incubated at 28°C for 48 h. After incubation, the petri dishes were examined for the presence of clear zones surrounding the colonies, indicating protease enzyme degradation (Malleswari and Bagyanarayan, 2013).

2.7 Production of cellulase

To evaluate the ability of the isolates to degrade cellulose, a cellulose-Congo red agar medium was prepared with a pH adjusted to 6.8. Petri dishes containing the medium were incubated at 30°C for 48 h. Following incubation, the presence of clear rings around and at the base of the colonies was assessed as an indicator of enzymatic cellulose degradation (Gupta *et al.,* 2012). The optical density of the reduced substances was measured using a SHIMADZU UV-1800 spectrophotometer at a wavelength of 530 nm. The concentration of reducing sugars was determined using a glucose calibration curve. For measuring cellulase activity, one unit was defined as the amount of enzyme that produces 1 mg of reduced substances, recalculated against glucose under the experimental conditions.

2.8 Antifungal activity of fungal endophytes

Endophytic fungal isolates were evaluated for their in vitro antifungal activity against several common phytopathogenic fungi, including *Fusarium moniliforme*, *Fusarium oxysporum*, *Fusarium vasinfectum*, and *Verticillium dahliae*. The fungi were cultivated in liquid PDA nutrient medium for 10 days, after which the cultures were centrifuged at 2500 rpm for 5 min to separate the supernatant. This supernatant was then used to inoculate petridishes, which were incubated at 28°C for 5 days until the control petri dishes were completely colonized by the fungi. The antifungal activity was assessed by measuring the width of the growth inhibition zone around the fungal colonies in the presence of the supernatant (Abro *et al.,* 2019).

2.9 Statistical analysis

The experimental data were analyzed using ANOVA in IBM SPSS Statistics 20. Duncan's multiple range tests was employed to identify significant differences, with the least significant difference set at a 5% level of significance ($p<0.05$).

3. Results

3.1 Isolation of endophytic fungi

Endophytic microorganisms have extensive interactions with plants. Fungi associated with these plants are commonly found in the phyllosphere (as epiphytes) and within plant tissues (as endophytes). Endophytes are primarily isolated from the leaves, stems, and roots of plants. They represent a particularly promising area of research, as they are integral to plant life and offer numerous beneficial effects. When selecting medicinal plants for the isolation of endophytic fungi, it is essential to consider their advantageous properties.In our study, we focused on the antibacterial activity of medicinal plants and isolated endophytic fungi from those exhibiting high antibacterial activity. We selected the *Lavandula* plant, which grows in our region and possesses medicinal properties (Figure 1). This plant is rich in endophytic fungi, yielding a total of four isolates from the leaves, two from the stems, and three from the roots, with nine isolates obtained from each variety. The isolated fungi were examined for their potential to promote plant growth by controlling phytopathogens, enhancing the production of phytohormones such as indole-3-acetic acid (IAA), cytokinins, and gibberellic acid, as well as facilitating plant growth through phosphate solubilization, nutrient cycling, and the secretion of novel bioactive metabolites.

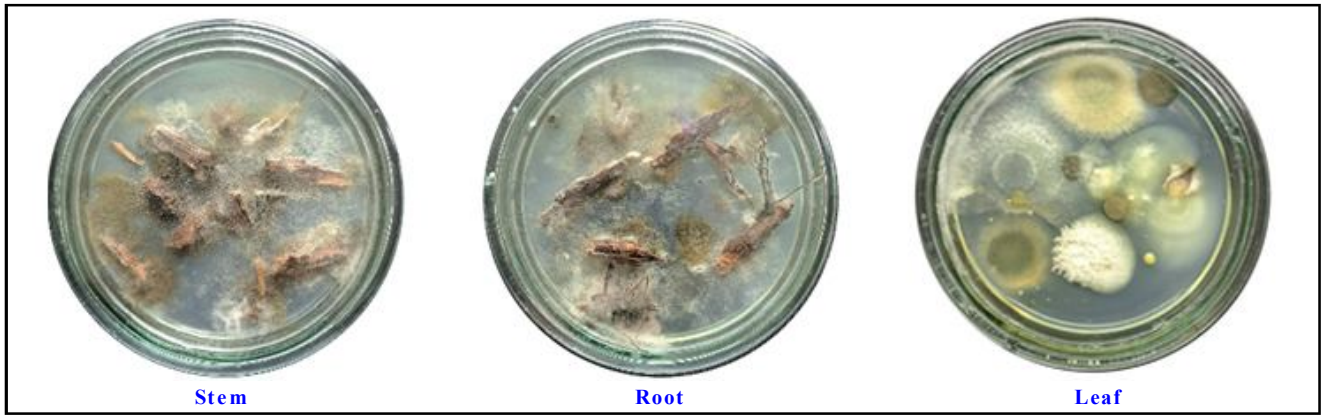

Figure 1: Isolation of endophytic fungi from Lavender.

According to our research, this is the first report detailing the description and investigation of the growth-promoting properties of endophytic fungi aimed at enhancing the growth performance of lavender plants in Uzbekistan.

3.2 Production of phytohormones by active isolates

Active endophytic fungal isolates were cultivated in Czapek DOX media to assess their production of gibberellic acid (GA) and indole acetic acid (IAA). The study revealed that the growth of the fungi, along with the activity and concentration of phytohormones, was significantly influenced by the conditions of the medium. The fungi were grown in liquid nutrient media for up to 7 days to determine which strains produced the highest amounts of GA and IAA over the growth period. Results showed that the production of phytohor-

mones increased with higher concentrations of cellulose and sucrose as carbohydrate sources. The highest synthesis of phytohormones was observed in nutrient media containing 1% sucrose and 2% cellulose. Specifically, the IAA synthesized by isolates LS2 and LR3 was 4.1 and 4.5 times greater, respectively, compared to the control, while the amounts of GA were 4.4 and 4.9 times higher. Notably, isolate LR3 produced the highest levels of IAA on the 5th and 6th days, yielding 1,224 mg/ml and 1,402 mg/ml, respectively. In comparison, the control produced 0.596 mg/ml on day 5 and 0.632 mg/ml on day 7 (Figure 2).

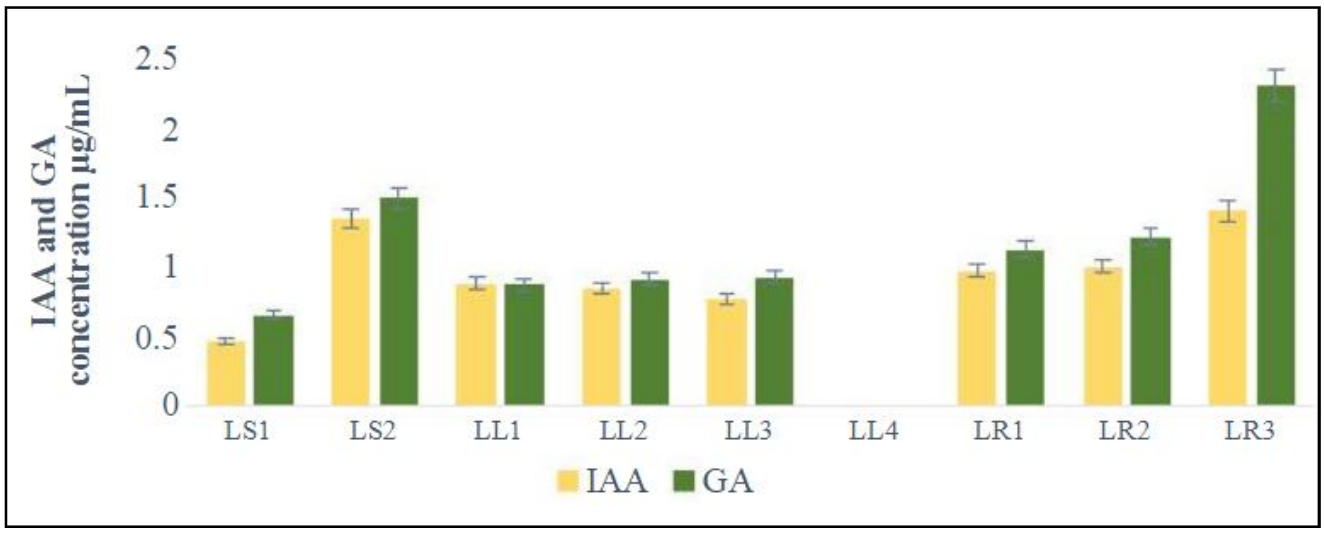

Figure 2: Quantitative production of IAA and GA by endophytic fungal isolates.

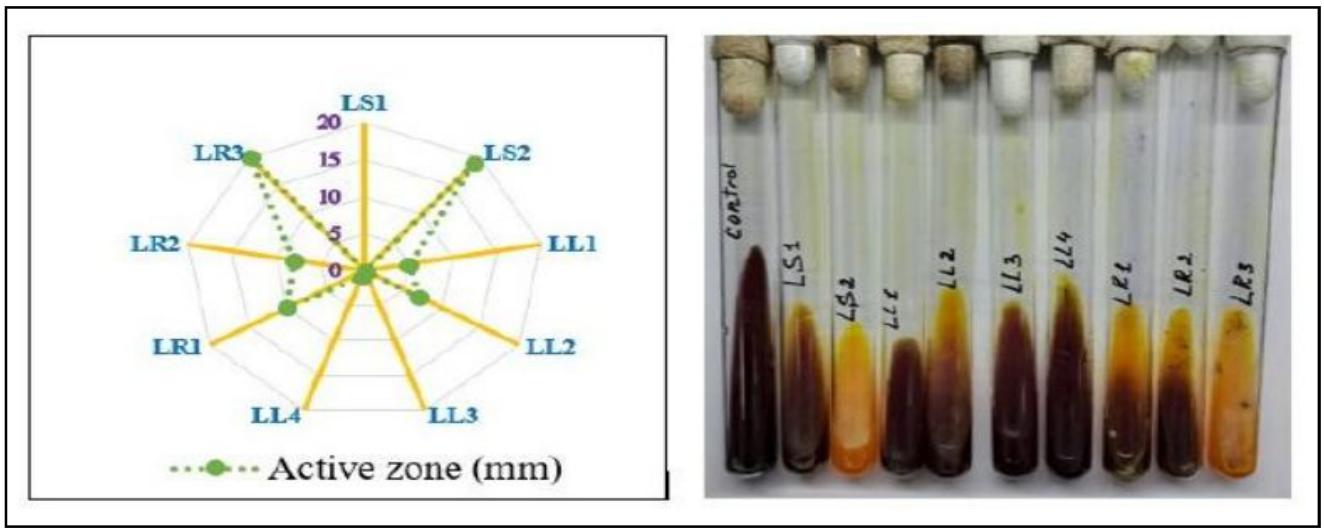

Figure 3: Phosphate solubilization of endophytic fungi.

3.3 Phosphate solubilizing activities of endophytic fungi

Phosphorus is a vital nutrient essential for the growth, development, and productivity of plants. In global agriculture, there is an increasing reliance on synthetic phosphorus fertilizers, alongside a recognition of the crucial role microbial communities play in enhancing plant phosphorus uptake. Fungi are particularly important as they can convert insoluble phosphates into soluble forms, facilitating mineralization. Phosphate-solubilizing fungi account for approximately 0.1-0.5% of the total fungal population in the soil, with endophytic fungi making a significant contribution to phosphate absorption. Therefore, we conducted an *in vitro* study to assess the ability of isolated endophytes to solubilize insoluble soil phosphorus.The results indicate that 33.3% of the nine isolated endophytic fungi, specifically isolates LS2, LR1, LR2, and LR3, exhibited activity zones measuring 19 mm, 12 mm, 9 mm, and 20 mm, respectively. Notably, isolates LS2 and LR3 demonstrated the highest rates of activity (Figure 3).

3.4 Plant growth-promoting traits

Siderophore production was detected in 66% of the endophytic fungi (Table 1), with the LS2 and LR3 isolates exhibiting the highest activity levels. To identify optimal conditions for lipase enzyme production by these endophytes, we investigated how variations in temperature and pH influence enzyme synthesis. Our findings revealed that the enzymatic activity of the three isolates grown in liquid tomato juice and Czapek DOX medium was significantly greater than that observed in Czapek DOX alone.

Table 1: General effect of isolated fungal isolates on beneficial properties of plants

Fungi isolates	Plant growth-promoting traits					
	P solubilization	IAA production	Siderophore production	Lipase	Protease	Cellulase
LS1	+	+	-	+	+	-
LS2	++	++	++	+	++	+
LL1	-	+	-	-	-	+
LL2	+	+	+	-	+	-
LL3	-	+	-	+	-	-
LL4	-	-	+	+	+	-
LR1	+	+	+	++	+	-
LR2	+	+	+	+	++	+
LR3	++	++	++	++	++	++

The research findings indicated that endophytic fungi cultivated in tomato juice were evaluated for the optimal temperature and pH values for lipase production. Lipase activity was observed to decline below 25°C and above 35 ± 2°C. In contrast, at a temperature of 28 ± 2°C, lipase synthesis was significantly enhanced (Table 2).

Among all the isolated fungi, four specifically demonstrated the ability to degrade filter paper. The results of the experiment indicated that the endo-1,4-β-glucanase and exo-1,4-β-glucanase enzyme activities produced by the LR3 isolate, which showed the highest rate of degradation, were measured at 4.22 and 3.12 units/mL, respectively. The next highest activities were observed in the LS2 isolate, recorded at 3.72 and 2.63 units/mL. Additionally, endo-1,4-β-glucanase activity was also detected in the LR2 isolate (Figure 4).

Table 2: Effect of temperature and pH on lipase production of selected endophytic fungi

S.No.	T (°C)	pH	Isolates endophytic fungi		
			LS2	LR2	LR3
				EA (U/ml)	
1	25	5	99.53 ± 4.82	125.3 ± 715	112.4 ± 6.97
2	28	5	107.2 ± 7.62	456.1 ± 2691	498.6 ± 31.92
3	35	5	21.8 ± 1.55	37.2 ± 2,83	56.3 ± 3.83
4	25	6	724.3 ± 41.28	987.64 ± 5136	1,745.7 ± 107.36
5	28	6	1812.3 ± 70.68	2489.2 ± 10703	2,627.9 ± 73.58
6	35	6	72.3 ± 5.78	89.7 ± 609	98.36 ± 6.28
7	25	7	668.6 ± 44.79	825.4 ± 4871	812.3 ± 57.68
8	28	7	1781.1 ± 76.58	2824.7 ± 107.34	2713.1 ± 124.81
9	35	7	193.7 ± 11.05	463.2 ± 31.88	494.8 ± 36.13

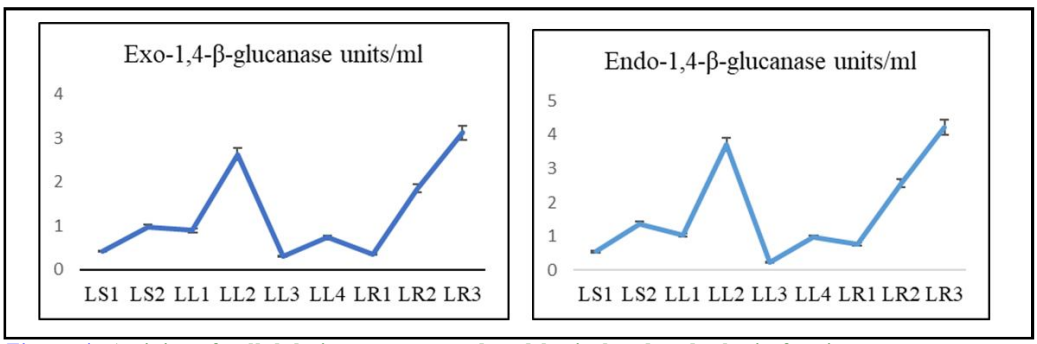

Figure 4: Activity of cellulolytic enzymes produced by isolated endophytic fungi.

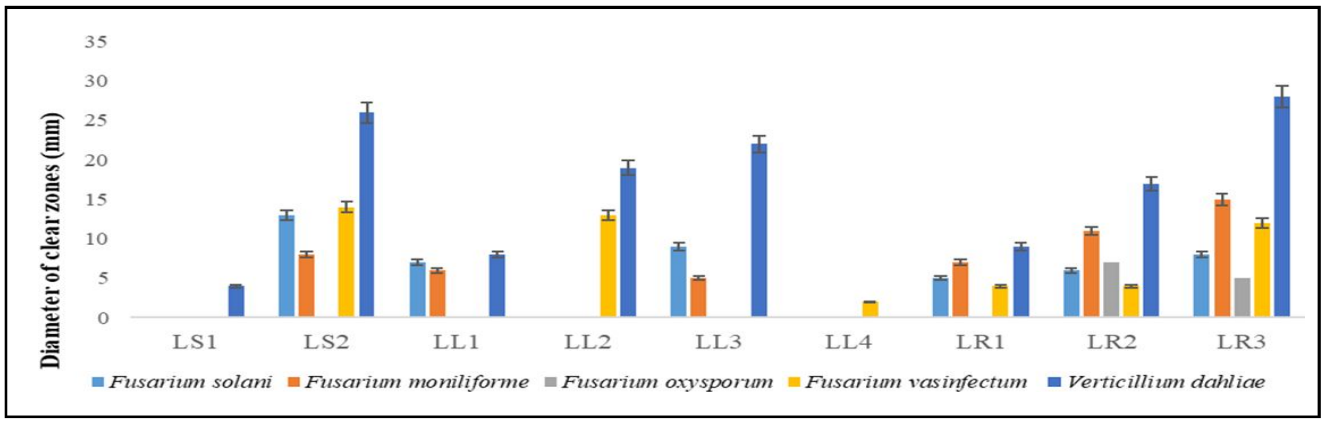

Figure 5: Antifungal properties of culture fluid of endophytes.

The results indicate that the isolates LL2 and LR3 synthesize the most active cellulolytic enzymes, effectively converting the substrate into a substantial amount of sugar.

3.5 Activity of isolated isolates against pathogenic fungi

Endophytes are recognized for their ability to produce antifungal metabolites, including steroids, quinones, alkaloids, terpenoids, isocoumarin derivatives, flavonoids, phenols, phenolic acids, and peptides. Accordingly, our subsequent experiments aimed to evaluate the antifungal properties of halotolerant endophytes. Initially, we cultured the endophytic fungi in a liquid nutrient medium for 10 days, after which the biomass was separated from the culture liquid through centrifugation. We then assessed the antifungal activity of the endophyte extracts and culture fluids against various plant pathogens, including *Fusarium solani*, *Fusarium moniliforme*, *Fusarium oxysporum*, *Fusarium vasinfectum*, and *Verticillium dahliae* (Figure 5).

As shown in this figure 5, when examining the antifungal properties of the endophyte culture fluids, no activity was observed against the plant pathogen *Fusarium oxysporum*. However, nearly 80% of the culture fluids exhibited varying levels of activity against other plant pathogens, specifically *Verticillium dahliae* and species of *Fusarium*.

4. Discussion

Endophytes colonize various parts of plants, including leaves, stems, and roots, and play a vital role in regulating metabolic processes related to plant growth and development, as well as in managing biotic and abiotic stresses. In this study, we isolated a total of nine endophytic fungal strains from lavender plants. These isolates enhance plant growth by controlling phytopathogens, producing phytohormones such as indole acetic acid (IAA), cytokinins, and gibberellic acids, solubilizing phosphates, cycling nutrients, and secreting bioactive metabolites. Garcia-Latorre and Poblaciones (2024) reported 42 fungal isolates from 20 different cultivars of Spanish lavender that demonstrated plant growth-promoting activities, including IAA synthesis, ammonia production, solubilization of phosphorus (P), potassium (K), and phytic acid, as well as tolerance to salinity stress. In our study, we found that stem and root endophytes were more abundant, leading to higher values of most plant growth-promoting parameters in endophytes sourced from shoots and roots. Endophytes isolated from the shoot (LS2) and root (LR3) exhibited the highest phosphate solubilization activity, while those from the leaves showed significantly lower activity. Most phosphate solubilizers are typically found in the soil and adjacent plant parts, such as roots and stems (Mehta *et al*., 2019). Consequently, many researchers focus on root fungal endophytes to investigate phosphate solubilization capacity across various plant species, including Himalayan yew (*Taxus wallichiana*) (Adhikari and Pandey, 2019), as well as capsicum, rice, cowpea, and maize (Surendirakumar *et al*., 2023).

Endophytic fungi are known to produce plant growth regulators like auxin, cytokinins and gibberellins (Baron and Rigobelo, 2022). Active isolates, grown in Czapek DOX media, produced significant amounts of gibberellic acid and indole acetic acid. Isolates LS2 and LR3 were particularly efficient, synthesizing IAA and GK at levels 4.1 to 4.9 times higher than controls, demonstrating their potential in promoting plant growth. Production of auxin and gibberellins were also found to be enhanced in fungal endophyte treated plants like rice, soybean and cucumber (Khan *et al.,* 2012; Khan *et al.,* 2008; Hamayun *et al.,* 2009). The optimization of temperature and pH conditions for lipase production by endophytes isolated from shoots (LS2) and roots (LR2 and LR3) revealed optimal values of 28°C and pH 7. Enzymes such as protease, lipase, and cellulase were found to be abundant in both root and shoot endophytes. These properties exhibited by endophytic fungi hold significant potential for biomolecular prospecting (Ghosh *et al.,* 2023). Patil *et al.* (2015) investigated the enzyme activities of amylase, protease, cellulase, and lipase in various endophytic fungal isolates derived from species including *Azadirachta indica*, *Citrus limon*, *Gossypium hirsutum*, *Magnolia champaca*, *Datura stramonium*, *Piper betle*, and *Phyllanthus emblica*. Endophytes isolated from various parts of the lavender plant demonstrated significant antifungal activity against *Verticillium dahliae*, with those sourced from the roots exhibiting the highest effectiveness against four different species of *Fusarium*. Notably, all isolates except for LR2 and LR3 showed no activity against *Fusarium oxysporum*, which is known to cause wilt disease in a variety of plant species (Jackson *et al.,* 2024). The secondary metabolites produced by endophytic fungi have promising applications in the pesticide industry, with antifungal biopesticides such as griseofulvin, carbendazim, imazalil, and trichothecene already commercialized (Xu *et al.,* 2021).

5. Conclusion

In this study, we isolated nine endophytic fungal strains from the lavender plant (*L. officinalis*). These fungi exhibit a diverse array of

plant growth-promoting characteristics, including the ability to solubilize phosphates and produce phytohormones such as indole acetic acid (IAA) and gibberellins (GA), as well as other metabolites including siderophores, proteases, lipases, and cellulases. Notably, four isolates: LS2, LR1, LR2, and LR3 demonstrated significantly enhanced activity in phosphate solubilization and the synthesis of IAA, siderophores, lipases, proteases, and cellulases compared to the remaining isolates. Furthermore, all fungal isolates exhibited varying degrees of antifungal activity against several pathogenic strains, including *Fusarium solani*, *Fusarium moniliforme*, *Fusarium oxysporum*, *Fusarium vasinfectum*, and *Verticillium dahliae*, with isolates LS2 and LR3 exhibiting particularly potent activity against multiple pathogens. This research aims to provide foundational knowledge for the development of eco-friendly biofertilizers utilizing these plant growth-promoting endophytic fungal isolates (LS2, LR1, LR2, and LR3) to enhance lavender yield and bolster plant resilience under adverse conditions.

Future prospects

The findings of this study underscore the considerable potential of endophytic fungi isolated from *L. officinalis* as biocontrol agents and biofertilizers. Future research should focus on the development of eco-friendly biofertilizers utilizing the plant growth-promoting isolates (LS2, LR1, LR2, and LR3), complemented by field trials to assess their effectiveness in enhancing lavender growth, yield, and resistance to both biotic and abiotic stresses. Investigating the mechanisms by which these endophytes promote plant growth and suppress phytopathogens will provide valuable insights into their roles within the plant microbiome. Additionally, exploring the characterization and applications of secondary metabolites produced by these endophytes could facilitate the development of novel antifungal biopesticides. Assessing the diversity of endophytic fungi across various lavender cultivars and environmental conditions may also reveal strains with superior plant growth-promoting properties. Finally, integrating these endophytic fungi with complementary agricultural practices, such as organic farming and precision agriculture, has the potential to optimize their benefits within sustainable farming systems, ultimately contributing to more resilient agricultural practices.

Acknowledgments

The authors would like to acknowledge the support provided by the Innovation Development Agency of the Ministry of Higher Education, Science and Innovation of Uzbekistan. Project Number FL-8323102106.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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Citation **Sokhibjon Abdusamatov, Dilfuza Jabborova, Jitendra Mehta, Krishnendra Singh Nama, Megha Barot and Baljeet Singh Saharan (2024). Exploring fungal endophytes in a medicinal plant, *Lavandula officinalis* L.: Isolation, characterization, and plant growth-promoting potential. Ann. Phytomed., 13(2):979-986. http://dx.doi.org/10.54085/ap.2024.13.2.101.**