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Antifungal Effects of *Funneliformis mosseae* and Plant Essential Oils in the Biological Management of *Fusarium* Wilt in Pepper (*Capsicum annuum* L.)

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ABSTRACT

This study presents the first comprehensive evaluation of the synergistic and antagonistic interactions between *Funneliformis mosseae* and plant essential oils in the biological control of *Fusarium oxysporum* in pepper. This research was conducted in two distinct stages, aiming to establish a viable biocontrol approach against the pathogen *Fusarium oxysporum* (Fo). Initially, under *in vivo* conditions, the disease mitigation potential of argan oil (Ao), black seed oil (Bo), and juniper oil (Jo) was assessed at concentrations of 1% and 3%, identifying the most potent concentration for subsequent experimentation. This study was conducted in a controlled climate chamber (temperature: 23 ± 2 °C, relative humidity: 60–70%, light-dark cycle: 14/10 h). Researchers investigated the effects of *Funneliformis mosseae* (Fm), alone and combined with selected essential oils, on the growth and disease severity of pepper (*Capsicum annuum* L.) plants. The treatments also resulted in significant increases in mycorrhizal colonization rates and spore densities in the soil. The data obtained showed that *F. mosseae* inoculation and the application of 3% black seed, juniper, and argan oil significantly increased the growth and biomass of pepper plants under *Fusarium oxysporum* stress. The Fo+Fm application reduced disease severity by 77% and increased root colonization, chlorophyll content, and nutrient uptake. However, the Fo+Bo+Fm combination only provided 54% suppression, demonstrating that the essential oil (Bo) antagonized AMF performance rather than enhancing it, resulting in lower root colonization, reduced chlorophyll content, and diminished nutrient uptake compared to Fo+Fm. Current findings show that the interaction between *F. mosseae* and plant essential oils is usually not synergistic. It depends on the specific compound and can even be antagonistic. The Fo+Bo+Fm combination resulted in less disease suppression and fewer physiological gains than Fo+Fm. This suggests that black seed oil can change the interaction from complementary to competitive. These variable responses emphasize that the ecological performance of AMF-essential oil combinations cannot be predicted in advance. Therefore, each essential oil type and concentration should be individually validated and evaluated under the specific plant–pathogen interaction conditions. These findings inform the optimization of sustainable agricultural practices and biological control strategies, laying the foundation for future studies at both the molecular and ecological levels.

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Biberde (*Capsicum annuum* L.) *Fusarium* Solgunluğunun Biyolojik Mücadelesinde *Funneliformis mosseae* ve Bitki Uçucu Yağların Antifungal Etkileri

ÖZET

Bu çalışma, biberde *Fusarium* oxysporum'un biyolojik kontrolünde *Funneliformis mosseae* ile bitkisel uçucu yağlar arasındaki sinerjistik ve antagonistik etkileşimleri bütüncül bir şekilde değerlendiren ilk araştırmadır. Bu araştırma, patojen *Fusarium oxysporum* (Fo)'a karşı

Bitki Koruma

Araştırma Makalesi

uygulanabilir bir biyolojik mücadele yaklaşımı oluşturmak amacıyla iki ayrı aşamada gerçekleştirilmiştir. İlk olarak, *in vivo* koşullar altında, argan yağı (Ao), çörek otu yağı (Bo) ve ardıç yağı (Jo) 'nun hastalık azaltma potansiyeli %1 ve %3 konsantrasyonlarda değerlendirilmiş ve sonraki aşama için en etkili konsantrasyon belirlenmiştir. Kontrollü iklimlendirme kabininde (23 ± 2 °C sıcaklık, %60–70 bağıl nem ve 14/10 saatlik aydınlık-karanlık döngü koşullarında) yürütülen çalışmada, Arbusküler Mikorizal Fungi *Funneliformis mosseae* (Fm)'nin, tek başına ve seçilen uçucu yağlarla kombinasyon halinde, biber (*Capsicum annuum* L.) bitkilerinin büyüme performansı ve hastalık şiddeti üzerindeki etkileri incelenmiştir. Ayrıca, uygulamalar sonucunda toprakta mikorizal kolonizasyon oranı ve spor yoğunluğunda belirgin artışlar kaydedilmiştir. Elde edilen veriler, *F. mosseae* inokülasyonu ve %3 çörek otu, ardıç ve argan yağı uygulamaları, *Fusarium oxysporum* stresi altındaki biber bitkilerinin büyümesini ve biyokütlesini önemli ölçüde artırdı. Fo+Fm uygulaması hastalık şiddetini %77 oranında azaltmış ve kök kolonizasyonu, klorofil içeriği ile besin alımını artırmıştır. Buna karşılık Fo+Bo+Fm kombinasyonu yalnızca %54 oranında baskılama sağlamış, bu durum, uçucu yağın (Bo) AMF'nin performansını artırmak yerine antagonize ettiğini, dolayısıyla kök kolonizasyonu, klorofil içeriği ve besin alımını Fo+Fm uygulamasına kıyasla daha düşük seviyelere indirdiğini göstermektedir. Mevcut bulgular, *F. mosseae* ile bitkisel uçucu yağlar arasındaki etkileşimin çoğu zaman sinerjik olmadığını ortaya koymaktadır. Bu etkileşim spesifik bileşiğe bağlıdır ve kimi durumlarda antagonistik dahi olabilmektedir. Fo+Bo+Fm kombinasyonu, Fo+Fm uygulamasına kıyasla daha düşük hastalık baskılama ve daha zayıf fizyolojik kazanımlar sağlamıştır. Bu durum, çörek otu yağının etkileşim dinamiğini tamamlayıcıdan rekabetçiye dönüştürebildiğini göstermektedir. Bu değişken yanıtlar, AMF–uçucu yağ kombinasyonlarının ekolojik performansının önceden genellenemeyeceğini vurgulamaktadır. Dolayısıyla, her bir uçucu yağ türü ve konsantrasyonu, ilgili bitki–patojen etkileşim koşullarında ayrı ayrı doğrulanmalı ve değerlendirilmelidir. Bu bulgular, sürdürülebilir tarım uygulamalarının ve biyolojik mücadele stratejilerinin optimize edilmesi için rehberlik sağlar ve moleküler ve ekolojik düzeylerde gelecekteki çalışmaların temelini oluşturur.

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INTRODUCTION

Pepper (*Capsicum annuum* L.) ranks among the most popular vegetables globally and is consumed fresh or processed. Its adaptability to a wide range of soil and climate conditions makes it one of the most economically important crops cultivated globally (Khaitov et al., 2019). Despite this resilience, several biotic stressors, especially soil-borne pathogens, pose serious threats to pepper productivity (Ahmad et al., 2023; Soylu et al., 2023; Güneş et al., 2024). Among these, *Fusarium oxysporum* is a key phytopathogen responsible for wilt disease, which adversely affects both yield and quality. The pathogen damages the plant's vascular system by obstructing nutrient and water transport, resulting in considerable crop losses as the infection progresses (Ahmad et al., 2023). Chemical fungicides have long been used to control plant diseases, but their application has raised concerns about environmental pollution, soil microbial imbalance, and the development of resistant pathogens (Kim & Hwang, 2007). As a result, interest in ecologically and environmentally friendly biological control techniques is growing within the framework of sustainable agricultural approaches. Biological control agents are attracting attention for their ability to prevent disease and support plant growth (Kamal et al., 2015).

Arbuscular mycorrhizal fungi (AMF), which increase nutrient uptake through symbiotic connections with plants, particularly *Funneliformis mosseae*, increase plant resistance to disease and stress (Wahab et al., 2023). These fungi colonize plant root systems and induce systemic resistance mechanisms that protect plants against infections, including those caused by *Fusarium* species (Shoresh et al., 2010). Additionally, biologically active molecules in the essential oils of plants, such as juniper, black seed, and argan, impart antifungal and antibacterial properties (Atay & Soylu, 2023). When applied to plants, these oils directly inhibit the growth of pathogens, thereby reducing disease load (Hegazy et al., 2025). Although the individual benefits of essential oils and arbuscular mycorrhizal fungi in plant protection are well documented, their synergistic interactions in pepper cultivation remain largely unexplored. To bridge this knowledge gap, a two-tiered experimental framework was developed to dissect the interactive effects of these biological agents on plant health and disease resistance (Manjunath et al., 2023). The study commenced with an *in vivo* assessment to determine the most effective concentration of selected essential oils for suppressing pathogenic stress. In a second, more controlled phase, the functional integration of the symbiotic fungi *F. mosseae* with the previously optimized essential oil treatments was subsequently investigated under climate-controlled chamber conditions. This approach enabled a nuanced evaluation of their combined influence on pepper plant physiology and their collective potential for managing soil-borne pathogens. Essential oils obtained from plants such as argan (*Argania spinosa*), black seed (*Nigella sativa*), and juniper (*Juniperus communis*) seeds contain a wide variety of bioactive chemicals with antibacterial properties (Moumou et al., 2024). Owing to their complex phytochemical compositions, which include terpenes, phenolics, and other volatile compounds, they exert multiple mechanisms of action against plant pathogens (Ninkuu et al., 2021). These include inhibiting spore germination, disrupting cell membranes, and blocking enzyme systems essential for pathogen survival. The use of these essential oils in agricultural settings has shown promising results in slowing the spread of diseases, altering host defense mechanisms, and even improving plant health through hormetic effects (Lorito et al., 1994; Soylu et al., 2010). In particular, the interaction of these essential oils with AMF offers a promising avenue for integrated disease control (Amani Machiani et al., 2023). AMF, especially *F. mosseae*, increase plant resilience to biotic stress by activating systemic immune responses and facilitating nutrient absorption (Wahab et al., 2023). Recent data suggest that the simultaneous application of essential oils and AMF may have synergistic effects (Rasouli et al., 2023). While essential oils can directly reduce the pathogen load, AMF-mediated immune signalling and root architecture modifications increase plant resilience. Additionally, certain phytochemicals present in essential oils may influence the dynamics of AMF colonization by altering the composition of the rhizosphere microbiota or root exudate profiles, which in turn may affect the formation and functionality of symbiotic relationships (Abkenar et al., 2023; Basaid & Furze, 2024).

Although theoretical evidence and isolated experimental data exist for these synergies, a comprehensive study on the mechanistic basis and agronomic effects of the combined application of essential oils and AMF in pepper systems is still lacking (Soussani et al., 2025). To fill this gap, the present study carefully examines how the interactions of argan, black seed, and juniper oils with *F. mosseae* affect the health of pepper plants in a controlled environment (Greff et al., 2023). To advance sustainable and efficient plant protection paradigms, this integrative approach aims to establish biological control frameworks that leverage the multifactorial interactions of microbial symbionts and botanical extracts. The hypotheses tested in the study are as follows:

Juniper, argan, and black seed essential oils have a protective effect against *Fusarium oxysporum* infection in pepper (*Capsicum annuum* L.) plants. Essential oils selected with *F. mosseae* support plant growth, strengthen immune responses, and increase disease suppression; this interaction may be synergistic. Essential oils can modulate symbiotic activity by affecting mycorrhizal activity and AMF colonization. Provide the fundamental scientific knowledge necessary to develop integrated biological management plans that reduce pathogen load in pepper plants. The main objective of this study is to investigate the synergistic and antagonistic effects of *F. mosseae* and selected essential oils on growth parameters and disease suppression in pepper plants infected with *Fusarium oxysporum.*

MATERIAL and METHOD

Materials

This study was conducted under both *in vitro* and *in vivo* conditions. During the experiment, pure essential oils approved for agricultural use and supported by analysis certificates were used. In this context, black seed oil, argan oil, and juniper oil were obtained from Botaniksan Tarım Sanayi Ticaret Limited Şirketi. Information about the chemical contents and quantities of the essential oils used is provided in Table 1 below.

In both phases of the study, the *Fusarium oxysporum* (FOYYU2) isolate, previously isolated from pepper plants and confirmed to be pathogenic, was obtained from the culture collection of the Plant Protection Department, Faculty of Agriculture, Van Yüzüncü Yıl University. The plant material used for the *in vivo* phase was seeds of a

registered local green pepper variety (cv. Sera Demre 8) provided by İklim Tarım Ürünleri A.Ş. (Mersin, Türkiye). Additionally, the arbuscular mycorrhizal fungi *F. mosseae* (T.H. Nicolson & Gerd.) (Schüßler & Walker, 2001). FMYYU1 (Fm), which was determined to exhibit high biological activity, was used as the inoculum material. The soil used in the study was obtained from the Gevaş district of Van Province (Van, Türkiye; 38°30′29.98″N, 43°11′31.78″E). The basic chemical and physical properties of the soil were determined as follows: pH value, 7.19; electrical conductivity (EC), 0.065 dS m^{-1}; organic matter content, 0.87/0.044; and lime content, 2.26%. Additionally, the soil fractions were measured as sand, 67.2%; clay, 17.6%; and silt, 15.2%. According to the USDA classification, this soil belongs to the "sandy loam" texture group.

Table 1. The chemical contents and quantities of the essential oils used
Çizelge 1. Kullanılan uçucu yağların kimyasal içerikleri ve miktarları

Essential Oils Used	Active ingredients	Average rate(%)	Amount
Black seed oil (20 ml)	Thymoquinone	27–48	0.1–0.18 g
	p-Cymene	7–15	0.026–0.058 g
	Thymohydroquinone	3-7	0.012–0.026 g
	α-Thujene	3-8	0.012–0.030 g
	Linoleic acid	55–65	0.20–0.24 g
	Oleic acid	20-25	0.07–0.09 g
	Palmitic acid	10-13	0.036–0.048 g
Argan oil (20 ml)	Oleic acid	43–50	8–9.5 g
	Linoleic acid	29–36	5.5–7 g
	Palmitic acid	11–15	2–3 g
	Stearic acid	4-7	0.7–1.3 g
	Tocopherols	600–900 mg/kg	10–18 mg
	Phenolic compounds	100–250 mg/kg	2-5 mg
	Squalene	300–450 mg/100 g	60–90 mg
Juniper oil (20 ml)	α-Pinene	20–50	3.5–9 g
	Sabinene	10–30	1.8–5.4 g
	ß-Pinene	5–15	0.9–2.7 g
	Myrcene	2–8	0.35–1.4 g
	Limonene	2–10	0.35–1.8 g
	Terpinen-4-ol	1-5	0.18–0.9 g

Design of experiment

In vitro

The first phase of the study was conducted under *in vitro* conditions at the Mycology Laboratory of the Plant Protection Department, Faculty of Agriculture, Van Yüzüncü Yıl University. The *F. oxysporum* isolate used in the experiments was propagated on potato dextrose agar (PDA) media and incubated for seven days under dark incubation conditions at 25°C. Antifungal activity tests were performed on PDA media supplemented with different essential oils. The tested concentrations were as follows: Positive control (PC), *F. oxysporum* grown only on PDA medium; Fo+Ao+%1, *F. oxysporum* combined with 1% argan oil; Fo+Ao+%3, *F. oxysporum* combined with 3% argan oil; Fo+Bo+%1, *F. oxysporum* combined with 1% black seed oil; Fo+Bo+3%, a combination of *F. oxysporum* with 3% black seed oil; Fo+Jo+1%, a combination of *F. oxysporum* with 1% juniper oil; and Fo+Jo+3%, a combination of *F. oxysporum* with 3% juniper oil. (Alaoui, 2020). The essential oils were dissolved in Tween 20 (0.5% v/v) to homogenize them and added to the PDA medium immediately before being poured into Petri dishes. The absence of a control group containing only Tween 20 in this experiment means that the potential effects of Tween 20 on the growth of *F. oxysporum* could not be evaluated, and this should be considered a limitation of the study. The prepared media were centrally inoculated with 5-mm-diameter agar discs obtained from *F. oxysporum* cultures in the active growth phase. Petri dishes were incubated in the dark at 25 °C, and the radial growth of the colonies was measured at seven time points, two days apart. Treatments were randomized according to a block design, and each treatment was planned to include five replicates. Measurements were taken using five replicate Petri dishes for each application concentration, and average colony diameters were calculated. The obtained values were converted to the mycelial growth inhibition percentage (MGI, %) (Alaoui, 2020) via equation [1] to determine the suppression rate of mycelial growth compared with that of the control group:

$$MGI\ (\%) = \left[\frac{dc-dt}{dc}\right] \times 100 \qquad \text{Eq. [1]}$$

Here, dc and dt represent the average mycelial diameters measured in the control group and treated environments, respectively. At the end of the 10th day after inoculation, the lowest concentration that completely inhibited mycelial growth for each essential oil was defined as the minimum inhibitory concentration (MIC).

In vivo

In the *in vivo* phase of the study, pepper seeds were disinfected in a 0.05% sodium hypochlorite (NaOCl) solution for 3 minutes and then thoroughly rinsed with distilled water (Ahmad et al., 2022). The seeds were sown in 45-cell plastic trays, each measuring 4.7 x 4.7 x 6.0 cm, and grown in climate conditions (23±2°C, 60–70% RH, and 14 h light / 10 h dark cycle) until seedling development. Soil obtained from the Gevaş district of Van province was used for seedling cultivation. Four weeks after sowing, the developing seedlings were transplanted into plastic pots with a diameter of 20 cm and a soil capacity of approximately 3 kg. Before transplanting, the pots were disinfected with a 10% formalin solution. The experiment was conducted following a randomized block design with five replicates, each consisting of a single plant. In applications where *F. mosseae* inoculation was performed, 10 g (150 spores per 1 g of soil) was added to each seedbed. In the control groups without AMF, sterilized quartz sand was used without the addition of any mycorrhizal inoculum.

The study was conducted in the climate chamber of the Faculty of Agriculture at Van Yüzüncü Yıl University. The plants were grown in a controlled-environment chamber maintained at 23 ± 2 °C and 60–70% relative humidity. A 16-hour light/8-hour dark cycle was applied, with LED growth lights providing illumination at intensities ranging from 6000 to 8000 lux.

Pepper seedlings that had developed in a climate-controlled environment for four weeks were inoculated with *F. oxysporum*. Before inoculation, 5 mm diameter discs were cut from *F. oxysporum* cultures propagated on PDA media via a fungal punch and transferred to a stock suspension solution. This suspension was adjusted to a spore density of $1x10^6$ conidia/mL via a hemocytometer. When the plants reached the three-leaf stage of development, the prepared *F. oxysporum* suspension was applied to each pot at a volume of 15 mL via the drenching method and was evenly distributed across the soil surface (Frans et al., 2017). No inoculation procedure was performed on the plants in the control group. Four days after pathogen inoculation, when the seedlings reached the four- to five-leaf phenological stage, each essential oil application was applied to the soil medium at a concentration of 3% per pot.

The experiment was designed in accordance with a randomized block design. A total of sixteen experimental groups were formed. A total of 80 plants were used in the study, with five replicates in each experimental group and one plant in each replicate. The study was terminated 21 days after pathogen inoculation, and the relevant parameters were checked.

Assessment of the Parameters

During harvest, the number of leaves (count), shoot length (ruler), root length (ruler), shoot diameter (digital caliper Insize, Chinese), and fresh weight (Radwag precision scale) were determined; then, the samples were dried in an oven at 70 °C for 48 hours to determine their dry weight (Radwag precision scale).

The dried plant samples were ground and subjected to dry combustion, and the resulting filtrates were analysed via the vanadomolybdophosphoric yellow color method with a spectrophotometer (Jenway 6505 UV/vis) to determine phosphorus values (ppm). The chlorophyll content of the cotton plants was assessed via a SPAD-502 Minolta SPAD.

Assessment of Disease Severity

Plants infected with *F. oxysporum* were assessed according to a 0–3 root and vascular discolouration scale (0: ¼ healthy roots; 1: ¼ slight browning (usually at the tip of the root); 2: ¼ moderate browning; and 3: ¼ severe browning) (Rasul, 2019).

The green part of the plant symptoms scale is as follows: 0 = no symptoms, 1 = slight stunting of the plant, wilting or drooping of a few leaves, 2 = stunting of the plant becomes more pronounced; chlorosis and some necrosis on the leaves, 3 = plant stunting is pronounced, with chlorosis and some necrosis accompanied by wilting/wilting, 4 = severe plant stunting and/or chlorosis and necrosis accompanied by leaf wilting, external brown discolouration on the stem, and 5 = plant death (Cerkauskas, 2017). Disease severity (DS) was determined following scale evaluations via the Townsend and Heuberger (1943) formula (Equation 2).

%Disease Severity = (Σ (Scale Value x Number of Plants)) / (Total Number of Plants x Highest Scale Value) x 100 Eq. [2]

The disease suppression rates (SR) of the treatment groups were calculated according to Equation 3, taking into account the percentages of disease severity:

$$SR(\%) = [\mathrm{DSp} - \mathrm{DS})/\mathrm{DSp}] \times 100 \quad \text{Eq. [3]}$$

Where DS denotes disease severity, and DSp denotes disease severity in the positive control group.

The colonization rate in roots (% AC) was obtained according to Equation (4). It was determined as a percentage (%) with the help of 5 (Giovanetti & Mosse, 1980).

$$AC\% = \left[\frac{ACR}{R}\right] x100 \quad \text{Eq. [4]}$$

Where ACR = number of roots colonized with AMF and R = total number of roots.

The dry weights of the plants with and without AMF were determined after an 8-week growth period. Mycorrhizal dependence (MD) in the dry weight of the plants was calculated according to Equation 5 (Declerck et al., 1995).

$$MD\% = [(A - B))/A]x100 \quad \text{Eq. [5]}$$

Where A represents the dry weight of AMF-inoculated plants, and B represents the dry weight of noninoculated plants.

The AMF spore densities in the rhizosphere soils of plants harboring AMF were determined via the wet sieving method developed by Gerdemann and Nicholson (1963).

Statistical Analysis

In vitro data were analyzed using IBM SPSS Statistics 28.0 software (IBM Corp., Armonk, NY, USA). The normality of the data distribution was assessed using the Shapiro-Wilk test, and the homogeneity of variance was assessed using the Levene test. The effects of treatments (Dose: Fo, Fo+Ao, Fo+Bo, Fo+Jo 1% and 3%) and measurement time (st, 7 measurements) on mycelial growth were evaluated using repeated measures ANOVA. Main effects (treatment and time) and interactions (Dose × st) were examined, and effect sizes were reported using Partial Eta Squared (η^2p). All results are presented as mean ± standard deviation (SD).

Data obtained under growth chamber conditions are presented as mean ± standard error (SE). Differences between treatments were evaluated using one-way ANOVA at the $p < 0.05$ level, followed by Duncan's multiple range test. Partial η^2 values were calculated to estimate effect sizes. Multivariate relationships between growth, physiological, disease, and mycorrhizal traits were analyzed using principal component analysis (PCA) and Pearson correlation coefficients. All analyses were performed using SPSS.

RESULTS

This study investigated the effects of *F. mosseae* and various essential oils (black seed, argan, and juniper oils) on the growth, physiological parameters, and disease suppression of pepper plants infected with *F. oxysporum*. Both single and combined treatments were evaluated *in vitro*, and the most effective oil concentration was determined to be 3% (Table 2)

Under climate chamber conditions, the severity of *F. oxysporum* disease in peppers, mycorrhizal colonization, photosynthesis, and plant growth dynamics were measured. These findings show that interactions between these biological agents play a key role in plant growth and disease prevention. The details of these parameters are presented in the following tables (Table 3, Table 4, Table 5, and Table 6).

In this study, the efficacy of various essential oils (juniper oil, argan oil, and black seed oil at 1% and 3% concentrations) against wilt disease caused by *F. oxysporum* was evaluated *in vitro* (Table 2). The results showed that applications with a 3% concentration were more effective at suppressing disease than were those with a 1% concentration. These findings suggest that the ability of essential oils to reduce phytopathogenic activity depends on the dose and concentration (Table 2). Repeated measures ANOVA results indicate that treatments have a significant effect on mycelial growth ($F(6,196) = 452.27$, $p < 0.001$, Partial $\eta^2 = 0.933$). The effect of measurement time was also significant and strong ($F(6,196) = 988.61$, $p < 0.001$, Partial $\eta^2 = 0.968$). The treatment × time interaction was also significant ($F(36,196) = 9.58$, $p < 0.001$, Partial $\eta^2 = 0.638$), indicating that treatments had different effects over time. All values are presented as mean ± standard deviation (SD). Significant differences were determined using ANOVA (Table 2).

The results in Table 2 show that the efficacy of essential oils changed significantly over time and exhibited a dynamic response pattern throughout the measurement periods. The time × treatment interaction was statistically significant ($p < 0.001$; Partial $\eta^2 = 0.638$), confirming that the antifungal activity of each oil changed depending on

Table 2. Effect of essential oils (black seed oil, argan oil, and juniper oil) at different concentrations (1% and 3%) on *F. oxysporum* wilt under *in vitro* conditions (mean ± standard deviation).

Çizelge 2. Farklı konsantrasyonlarda (1% ve 3%) uçucu yağların (çörek otu yağı, argan yağı ve ardıç yağı) in vitro koşullar altında F. oxysporum solgunluğuna etkisi (Standart sapma)

Treatments	1st meas.	2st meas.	3st meas.	4st meas.	5st meas.	6st meas.	7st meas.
	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D	$\bar{x}$ ± S.D
Fo (PC)	1.82 ± 0.21^{Ea}	2.32 ± 0.19^{Da}	2.90 ± 0.20^{Ca}	3.42 ± 0.25^{Ca}	4.00 ± 0.16^{Ba}	4.54 ± 0.23^{ABa}	5.06 ± 0.13^{Aa}
Fo+Ao 1%	0.60 ± 0.15^{Dc}	1.02 ± 0.17^{C}	1.38 ± 0.22^{Cc}	1.68 ± 0.19^{Bc}	1.92 ± 0.22^{Bcd}	2.16 ± 0.23^{ABc}	2.44 ± 0.26^{Ac}
Fo+Ao 3%	0.54 ± 0.11^{Dc}	0.94 ± 0.11^{Cc}	1.24 ± 0.15^{Cd}	1.44 ± 0.08^{Cd}	1.64 ± 0.08^{Bd}	1.88 ± 0.44^{ABd}	2.24 ± 0.13^{A}
Fo+Bo 1%	0.90 ± 0.22^{Eb}	1.30 ± 0.18^{Eb}	1.84 ± 0.15^{Db}	2.38 ± 0.19^{Cb}	2.82 ± 0.16^{Bb}	3.32 ± 0.22^{ABb}	3.90 ± 0.07^{Ab}
Fo+Bo 3%	0.76 ± 0.18^{Fbc}	1.12 ± 0.21^{Eb}	1.72 ± 0.31^{Db}	2.16 ± 0.24^{Cb}	2.68 ± 0.25^{Cbc}	3.18 ± 0.20^{Bb}	3.68 ± 0.20^{Ab}
Fo+Jo 1%	0.68 ± 0.14^{Cbc}	1.20 ± 0.15^{BCb}	1.68 ± 0.16^{Bbc}	2.14 ± 0.16^{Bb}	2.62 ± 0.22^{Bbc}	3.18 ± 0.19^{ABb}	3.72 ± 0.16^{Ab}
Fo+Jo 3%	0.54 ± 0.11^{Ec}	1.02 ± 0.08^{DEb}	1.58 ± 0.08^{Dbc}	2.08 ± 0.13^{Cb}	2.52 ± 0.13^{BCc}	3.08 ± 0.8^{Bb}	3.64 ± 0.11^{Ab}
Partialη^2 (Dose)	0.933	0.933	0.933	0.933	0.933	0.933	0.933
Partialη^2 (st)	0.968	0.968	0.968	0.968	0.968	0.968	0.968
Partialη^2 (Dose×st)	0.638	0.638	0.638	0.638	0.638	0.638	0.638

Fo: *Fusarium oxysporum,* Ao: Argan oil, Bo: Black seed oil, Jo: Juniper oil, Fo (PC): positive control. Different letters in the same column indicate statistically significant differences (Tukey HSD test, $p < 0.05$). Partial η^2 values indicate the effect sizes of the main factors and interaction factors. Uppercase letters display measurement data over time from right to left, while lowercase letters display time-dependent changes in applications from top to bottom.

Table 3. Effects of *F. mosseae* and black seed, juniper, and argan oils on root length (cm), shoot length (cm), total fresh weight (g), and total dry weight (g) in pepper plants infected with *F. oxysporum* (mean ± standard error).

Çizelge 3. F. mosseae ve çörek otu, ardıç ve argan yağlarının F. oxysporum ile enfekte olmuş biber bitkilerinde kök uzunluğu (cm), sürgün uzunluğu (cm), toplam taze ağırlık (g) ve toplam kuru ağırlık (g) üzerindeki etkileri (ortalama ± standart hata).

Treatments	Root Length (cm)	Shoot Length (cm)	Total Fresh Weight (g)	Total Dry Weight (g)
	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E
Control	14.20 ± 1.65^{DE}	37.20 ± 2.46^{CD}	20.40 ± 1.38^{BC}	3.51 ± 0.20^{B}
Fo	13.00 ± 1.65^{E}	35.40 ± 2.46^{D}	18.12 ± 1.38^{C}	3.00 ± 0.20^{B}
Fm	23.40 ± 1.65^{AB}	$44.40\pm2.46^{A-C}$	21.32 ± 1.38^{BC}	4.11 ± 0.20^{A}
Ao	$18.60\pm1.65^{B-D}$	$41.20\pm2.46^{B-D}$	23.41 ± 1.38^{AB}	3.91 ± 0.20^{A}
Bo	$17.20\pm1.65^{C-E}$	$44.00\pm2.46^{A-C}$	21.23 ± 1.38^{BC}	3.84 ± 0.20^{A}
Jo	15.20 ± 1.65^{DE}	38.40 ± 2.46^{-CD}	21.07 ± 1.38^{BC}	3.66 ± 0.20^{A}
Fo+ Fm	$18.00\pm1.65^{C-E}$	$43.80\pm2.46^{A-C}$	26.45 ± 1.38^{A}	4.08 ± 0.20^{A}
Ao + Fm	$16.80\pm1.65^{C-E}$	$39.00\pm2.46^{B-D}$	$22.18\pm1.38^{A-C}$	3.73 ± 0.20^{A}
Bo+ Fm	$18.80\pm1.65^{B-D}$	$40.20\pm2.46^{B-D}$	21.57 ± 1.38^{BC}	3.92 ± 0.20^{A}
Jo + Fm	16.00 ± 1.65^{DE}	38.40 ± 2.46^{CD}	21.48 ± 1.38^{BC}	3.69 ± 0.20^{A}
Fo+ Ao	26.20 ± 1.65^{A}	$41.80\pm2.46^{A-D}$	19.98 ± 1.38^{BC}	3.71 ± 0.20^{A}
Fo+ Bo	$21.80\pm1.65^{A-C}$	$41.60\pm2.46^{A-D}$	23.37 ± 1.38^{AB}	3.63 ± 0.20^{A}
Fo+ Jo	$19.40\pm1.65^{B-D}$	$39.60\pm2.46^{B-D}$	21.05 ± 1.38^{BC}	3.66 ± 0.20^{A}
Fo+ Ao + Fm	$17.80\pm1.65^{C-E}$	47.00 ± 2.46^{AB}	$21.96\pm1.38^{A-C}$	4.06 ± 0.20^{A}
Fo+ Bo + Fm	16.00 ± 1.65^{DE}	49.40 ± 2.46^{A}	$21.99\pm1.38^{A-C}$	3.97 ± 0.20^{A}
Fo+ Jo + Fm	$18.80\pm1.65^{B-D}$	$43.60\pm2.46^{A-D}$	$22.06\pm1.38^{A-C}$	3.79 ± 0.20^{A}
$p^{treatment}$	$p^{0.000}$	$p^{0.014}$	$p^{0.087}$	$p^{0.047}$
Partial η^2 (*treatment)*	0.496	0.344	0.278	0.302

Fo: *Fusarium oxysporum,* Fm*: Funneliformis mosseae,* Ao: Argan oil, Bo: Black Seed Oil, Jo: Juniper oil, *P^n: P value indicating the importance level.* Duncan's multiple comparison test was performed, and the difference between the treatment groups marked with the same letter was not significant at $p<0.05$. Partial η^2 values indicate the effect sizes of the main factors and interaction factors.

Table 4. Effects of *F. mosseae* and black seed, juniper, and argan oil application on shoot diameter (mm), number of leaves (number), phosphorus content (mg kg¹), and total chlorophyll in pepper plants in response to *F. oxysporum* infection (mean ± standard error).

Çizelge 4. F. oxysporum enfeksiyonuna yanıt olarak F. mosseae ve çörek otu, ardıç ve argan yağı uygulamasının biber bitkilerinde sürgün çapı (mm), yaprak sayısı (sayı), fosfor içeriği (mg kg¹) ve klorofil üzerindeki etkileri (ortalama ± standart hata).

Treatments	Shoot Diameter (mm)	Number of Leaves (number/plant)	P (ppm)	Chl. (SPAD)
	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E
Control	4.87±0.20 ^{A}	30.20±1.30 ^{C}	4371.65±324.65^{A}	29.14±1.05^{E}
Fo	4.76±0.20 ^{A}	21.40±1.30 ^{D}	2721.18±324.65 $^{B-E}$	29.90±1.05^{E}
Fm	5.03±0.20 ^{A}	41.20±1.30^{AB}	2298.12±324.65 ^{DE}	36.27±1.05^{CD}
Ao	4.90±0.20 ^{A}	32.00±1.30 ^{C}	3771.31±324.65 ^{AB}	40.90±1.05^{AB}
Bo	4.91±0.20 ^{A}	39.40±1.30 ^{AB}	3290.49±324.65 $^{B-D}$	37.06±1.05^{CD}
Jo	4.87±0.20 ^{A}	33.40±1.30 ^{C}	3648.26±324.65 $^{A-C}$	36.42±1.05^{CD}
Fo+ Fm	4.90±0.20 ^{A}	37.40±1.30 ^{B}	1263.96±324.65^{F}	39.26±1.05^{BC}
Ao + Fm	4.95±0.20 ^{A}	33.60±1.30 ^{C}	2919.66±324.65 $^{B-D}$	40.34±1.05^{AB}
Bo+ Fm	4.92±0.20 ^{A}	32.20±1.30 ^{C}	2903.99±324.65^{B-D}	42.62±1.05^{A}
Jo + Fm	4.94±0.20 ^{A}	31.0±1.30 ^{C}	2627.17±324.65 $^{C-E}$	42.42±1.05^{AB}
Fo+ Ao	4.95±0.20 ^{A}	32.00±1.30 ^{C}	2689.84±324.65 $^{B-E}$	37.00±1.05^{CD}
Fo+ Bo	4.95±0.20^{A}	30.80±1.30 ^{C}	1748.66±324.65 $^{E-F}$	35.32±1.05^{D}
Fo+ Jo	4.93±0.20 ^{A}	30.20±1.30 ^{C}	2470.48±324.65 ^{DE}	35.22±1.05^{D}
Fo+ Ao + Fm	5.18±0.20 ^{A}	41.80±1.30 ^{A}	3081.57±324.65 $^{B-D}$	42.82±1.05^{A}
Fo+ Bo + Fm	5.28±0.20 ^{A}	41.00±1.30 ^{AB}	3139.02±324.65 $^{B-D}$	42.70±1.05^{A}
Fo+ Jo + Fm	5.09±0.20 ^{A}	41.20±1.30 ^{AB}	2804.75±324.65 $^{B-D}$	42.08±1.05^{AB}
$p^{treatment}$	$p^{0.980}$	$p^{0.000}$	$p^{0.000}$	$p^{0.000}$
Partial η^2 (treatment)	0.081	0.812	0.555	0.801

Fo: *Fusarium oxysporum,* Fm*: Funneliformis mosseae,* Ao: Argan oil, Bo: Black Seed Oil, Jo: Juniper oil, P: Phosphorus, Chl.: Amount of chlorophyll

P^{n}*: P value indicating the importance level.* Duncan's multiple comparison test was performed, and the difference between the treatment groups marked with the same letter was not significant at $p<0.05$. Partial η^2 values indicate the effect sizes of the main factors and interaction factors.

Table 5. Effects of *Fusarium oxysporum* infection, *Funneliformis mosseae* inoculation, and essential oil applications (black seed, juniper, and argan oils) on the photosynthetic rate (%) and photosynthetic R value of pepper plants (mean ± standard error).

Çizelge 5. Fusarium oxysporum enfeksiyonuna karşı Funneliformis mosseae ile birlikte çörek otu, ardıç ve argan yağı uygulamalarının biber bitkilerinde fotosentetik oran (%) ve fotosentetik R değeri üzerindeki etkileri (ortalama ± standart hata).

Treatments	Photosynthetic rate (%)	Photosynthetic R value
	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E
Control	95.40±0.46 ^{A}	1.00±0.26 ^{A}
Fo	95.60±0.46 ^{A}	1.60±0.26 ^{A}
Fm	95.48±0.46 ^{A}	1.80±0.26 ^{A}
Ao	95.94±0.46 ^{A}	1.40±0.26 ^{A}
Bo	96.02±0.46 ^{A}	1.26±0.26 ^{A}
Jo	95.04±0.46 ^{A}	1.80±0.26 ^{A}
Fo+ Fm	95.70±0.46 ^{A}	1.60±0.26 ^{A}
Ao + Fm	96.32±0.46 ^{A}	1.00±0.26 ^{A}
Bo+ Fm	96.44±0.46 ^{A}	1.80±0.26 ^{A}
Jo + Fm	96.20±0.46 ^{A}	1.40±0.26 ^{A}
Fo+ Ao	95.54±0.46 ^{A}	1.60±0.26 ^{A}
Fo+ Bo	95.90±0.46^{A}	1.80±0.26^{A}
Fo+ Jo	96.32±0.46 ^{A}	1.00±0.26 ^{A}
Fo+ Ao + Fm	96.26±0.46 ^{A}	1.00±0.26 ^{A}
Fo+ Bo + Fm	95.98±0.46 ^{A}	1.20±0.26 ^{A}
Fo+ Jo + Fm	96.12±0.46 ^{A}	1.40±0.26 ^{A}
$p^{treatment}$	$p^{0.575}$	$p^{0.160}$
Partial η^2 (treatment)	0.173	0.251

Fo: *Fusarium oxysporum,* Fm*: Funneliformis mosseae,* Ao: Argan oil, Bo: Black Seed Oil, Jo: Juniper oil. *P*^{n}*: P value indicating the importance level.* Duncan's multiple comparison test was performed, and the difference between the treatment groups marked with the same letter was not significant at $p<0.05$. Partial η^2 values indicate the effect sizes of the main factors and interaction factors.

Table 6. Effects of black seed, juniper, and argan oils applied together with *F. mosseae* on the degree of root colonization (%), spore density in the soil (spores/g soil), and mycorrhizal dependency rate (%) in pepper plants infected with *F. oxysporum* (mean ± standard error)

Çizelge 6. F. mosseae ile birlikte uygulanan çörek otu, ardıç ve argan yağlarının, F. oxysporum ile enfekte olmuş biber bitkilerinde kök kolonizasyon derecesi (%), toprakta spor yoğunluğu (spor/g toprak) ve mikorizal bağımlılık oranı (%) üzerindeki etkileri (ortalama ± standart hata)

Treatments	RC (%)	SDS (spore/g soil)	MD (%)
	$\bar{x}$ ± S.E	$\bar{x}$ ± S.E	
Fm	84.00±7.07^{A}	13.80±0.59^{B}	14.59
Fo+ Fm	89.00±7.07^{A}	7.40±0.59^{E}	26.47
Ao + Fm	75.00±7.07^{AB}	14.00±0.59^{B}	-4.82
Bo+ Fm	36.00±7.07^{D}	17.80±0.59^{A}	2.04
Jo + Fm	54.00±7.07^{BD}	14.00±0.59^{B}	0.81
Fo+ Ao + Fm	70.00±7.074^{AB}	11.80±0.59^{C}	8.62
Fo+ Bo + Fm	40.00±7.07^{CD}	13.40±0.59^{BC}	8.56
Fo+ Jo + Fm	61.00±7.07^{BC}	10.00±0.59^{D}	3.43
$p^{treatment}$	$p^{0.000}$	$p^{0.000}$	
Partial η^2 (treatment)	0.624	0.855	

Fo: *Fusarium oxysporum,* Fm*: Funneliformis mosseae,* Ao: Argan oil, Bo: Black Seed Oil, Jo: Juniper oil, RC: Root colonization, SDS: spore density in the soil, MD: Mycorrhizal dependency rate, P^n*: P value indicating the importance level.* Duncan's multiple comparison test was performed, and the difference between the treatment groups marked with the same letter was not significant at $p<0.05$. Partial η^2 values indicate the effect sizes of the main factors and interaction factors.

The exposure time. The 1% juniper oil (Fo+Jo 1%) treatment showed the least inhibition, with an average colony diameter of 3.72 ± 0.16 cm (Table 2), while the 3% argan oil (Fo+Ao 3%) application showed the strongest inhibitory effect, reducing mycelial growth to 2.24 ± 0.13 cm at the final measurement (day 7). Higher amounts of essential oils had greater inhibitory effects on the mycelial growth of *F. oxysporum*, indicating the dose-dependent antifungal activity of essential oils. As indicated by high partial η^2 values (0.933–0.968) and statistical analysis confirming significant differences between treatments ($p < 0.001$), both treatment type and concentration explained a large portion of the variance in mycelial development. These results clearly show that increasing the concentration of essential oils improves the suppression of *F. oxysporum* development, depending on the concentration. Overall, the biological efficacy of the applied essential oils was significantly affected by both concentration and exposure time (Table 2).

The data in Table 3 clearly show the different levels of effectiveness of *F. mosseae* and various essential oils in alleviating the wilting stress caused by *F. oxysporum* in pepper plants. Compared to the pathogen-inoculated group (Fo), Fm application significantly increased root and shoot growth, with root length reaching 23.40 cm (approximately 80% more than Fo) and shoot length reaching 44.40 cm (a 25% increase, $p<0.05$). These results highlight the capacity of arbuscular mycorrhizal fungi to enhance plant tolerance mechanisms under pathogenic stress conditions (Table 3).

Additionally, compared to the control group, the combined application of Ao+Fm and Bo+Fm showed significant improvements in overall growth performance. Despite *Fusarium* infection, Fo+Fm and Fo+Bo applications yielded the highest total fresh weight (26.45 g and 23.37 g, respectively) and exceeded the control group by up to 29% ($p<0.05$). A similar pattern was observed for total dry weight; Fo+Fm (4.08 g) and Fo+Bo (3.63 g) yielded the highest biomass values and showed a significant increase in physiological vitality. Specifically, the Fo+Bo+Fm combination increased dry biomass by approximately 19% compared to the use of Fo alone, indicating a strong synergistic interaction between mycorrhizal fungi and black seed oil. This synergy likely stems from the integrated effects of mycorrhizal colonization and the bioactive antifungal components of volatile oils; these components jointly alleviate disease-induced oxidative and physiological stress ($p<0.05$) (Table 3).

However, not all combinations provided similar benefits. Treatments such as Fo+Ao+Fm and Fo+Jo+Fm failed to significantly improve fresh and dry weights ($p>0.05$). These differences can be attributed to the different chemical compositions and bioactivity profiles of the essential oils, as well as their different interactions with mycorrhizal symbiosis. Overall, the findings highlight the potential of *F. mosseae* as a biologically sustainable strategy to reduce *Fusarium* wilt and enhance plant growth and productivity, either alone or in targeted combinations with compatible essential oils (Table 3).

As shown in Table 4, *Fusarium* infection (Fo) caused significant decreases in shoot diameter, leaf number, and phosphorus content ($p<0.05$), confirming its inhibitory effect on plant physiology. In contrast, *F. mosseae* (Fm) significantly increased growth and raised the number of leaves per plant to 41.20, which is nearly double that of

Fo (21.40) (Table 4).

Among the essential oils, black seed oil (Bo) showed the highest phosphorus concentration (3707.31 mg kg^{-1}), followed by juniper oil (3634.41 mg kg^{-1}). Both are significantly higher than the infected control group ($p<0.05$). The Fo+Bo combination reached the maximum shoot diameter (4.95 mm), indicating a clear synergistic interaction under pathogen stress. Specifically, triple combinations such as Fo+Ao+Fm (42.82 SPAD) and Fo+Bo+Fm (42.70 SPAD) produced the highest total chlorophyll content, approximately 45% higher than the control group (29.14 SPAD), indicating an increase in photosynthetic capacity (Table 4).

In general, these findings indicate that the application of *F. mosseae* in combination with compatible essential oils, particularly black seed and argan oils, effectively improves nutrient uptake and chlorophyll synthesis, thereby enhancing plant resistance to *Fusarium*-induced stress (Table 4).

As shown in Table 5, neither *Fusarium* infection nor the application of *F. mosseae* and essential oils alone or in combination significantly affected the photosynthetic parameters of pepper plants ($p>0.05$). Photosynthetic rate values remained relatively constant, ranging from 95.04% (Jo) to 96.44% (Bo+Fm), indicating that the applications did not impair photosynthetic efficiency (Table 5). Similarly, photosynthetic R values showed only slight fluctuations (1.00–1.80), with the highest average value recorded in the Fm, Jo, and Fo+Bo applications (1.80).

These minimal changes indicate that both pathogen and bioinoculant applications maintained photosynthetic stability and reflected a balanced physiological response under *Fusarium* stress conditions (Table 5). Overall, the results indicate that the combined use of *F. mosseae* and essential oils preserves photosynthetic performance. This suggests that the applications effectively reduce stress effects without impairing the carbon assimilation capacity of pepper plants (Table 5).

As shown in Table 6, the interaction between *F. mosseae* and essential oils had a significant effect on root colonization (RC), soil spore density (SDS), and mycorrhizal dependence (MD) in pepper plants infected with *Fusarium* ($p<0.001$).

The Fo+Fm treatment had the highest root colonization rate (89%), followed by Fm alone (84%). This suggests that the pathogen may promote mycorrhizal development as a defense strategy. Interestingly, when black seed oil (Bo) and fo were applied together, colonization decreased significantly to 36%, indicating that Bo inhibits AMF colonization. These findings indicate that, despite the pathogen's stimulatory effect, Bo has an antagonistic effect on the development of the symbiotic relationship between AMF and the host plant (Table 6).

In contrast, Bo+Fm caused the lowest colonization rate (36%) and the highest spore density in soil (17.80 spores g^{-1}), indicating that root infection activity was limited despite the abundance of propagules. Among the triple combinations, Fo+Jo+Fm (61%) and Fo+Ao+Fm (70%) maintained moderate colonization levels but showed significant decreases in spore density (10.00 and 11.80 spores g^{-1}, respectively), reflecting an increase in symbiotic balance (Table 6).

The highest mycorrhizal dependency (MD), reflecting a strong AMF contribution, was observed in Fo+Fm (26.5%), Fm alone showed moderate MD (14.6%), and application with essential oils significantly reduced MD (Ao+Fm: 4.8%, Bo+Fm: 2.0%, Fo+Ao+Fm: 8.6%) and showed antagonistic effects on AMF activity (Table 6). Overall, these findings indicate that the compatibility between *F. mosseae* and essential oils strongly influenced colonization dynamics and that the Fo+Fm combination was the most effective method for maintaining symbiosis and improving root-fungus interaction under *Fusarium* stress (Table 6).

Table 7 shows that *F. oxysporum* causes the highest disease severity (2.60 ± 0.28) in pepper plants, confirming the pathogen's strong negative effect. Inoculation with *F. mosseae* (Fo+Fm) reduced disease severity to 0.80, providing 77% suppression based on stem diameter and 69% suppression based on green shoot evaluation, highlighting the fungi's protective role. Combinations with essential oils, particularly Fo+Bo and Fo+Jo+Fm, also reduced disease severity, providing up to 54% inhibition and demonstrating a synergistic interaction between AMF and certain oils. In contrast, Fo+Ao and Fo+Ao+Fm were less effective, providing only 8-15% suppression, suggesting that argan oil may be less compatible with the protective effect of *F. mosseae* under the applied conditions (Table 7).

These results indicate that the integration of *F. mosseae* with suitable essential oils not only reduces pathogen-induced damage but may also enhance the plant's overall resistance. The findings indicate that selecting compatible AMF-oil combinations is crucial for optimizing disease control and that black seed and juniper oils are particularly effective partners for supporting mycorrhizal-mediated defense against *Fusarium* wilt in pepper plants.

The PCA results (Table 8) reveal the relative contributions of different plant and soil parameters to the variability in the dataset. The first principal component (PCA-1) explained 38.13% of the total variance; shoot length (SL, 0.830), leaf number (LN, 0.858), dry weight (DW, 0.899), and chlorophyll content (Chl, 0.835). This indicates that plant growth and biomass traits are the main factors distinguishing the applications (Table 8).

Table 7. Effects of *F. mosseae* and essential oils (black seed, juniper, and argan) on disease severity (%) and disease suppression rates (%) in pepper exposed to *F. oxysporum* stress (mean ± standard error)

Çizelge 7. F. mosseae ve uçucu yağların (çörek otu, ardıç ve argan) F. oxysporum stresine maruz kalan biberlerde hastalık şiddeti (%) ve hastalık bastırma oranları (%) üzerindeki etkileri (ortalama ± standart hata)

Treatments	DS* (%)	Inh.*(%)	DS **(%)	Inh.**(%)
	$\bar{x} \pm$ S.E		$\bar{x} \pm$ S.E	
Fo	2.60 ± 0.28^{A}		2.60 ± 0.35^{A}	
Fo+ Fm	0.80 ± 0.28^{D}	77	0.60 ± 0.35^{C}	69
Fo+ Ao	2.40 ± 0.28^{AB}	8	2.40 ± 0.35^{A}	8
Fo+ Bo	1.20 ± 0.28^{CD}	54	1.20 ± 0.35^{BC}	54
Fo+ Jo	2.20 ± 0.28^{AB}	-8	2.80 ± 0.35^{A}	15
Fo+ Ao + Fm	2.00 ± 0.28^{AC}	15	2.20 ± 0.35^{AB}	23
Fo+ Bo + Fm	1.60 ± 0.28^{BD}	0	2.60 ± 0.35^{A}	38
Fo+ Jo + Fm	1.20 ± 0.28^{CD}	15	2.20 ± 0.35^{AB}	54
$p^{treatment}$	$p^{0.000}$		$p^{0.000}$	
Partial η^2 (treatment)	0.855		0.510	

Fo: *Fusarium oxysporum,* Fm*: Funneliformis mosseae,* Ao: Argan oil, Bo: Black Seed Oil, Jo: Juniper oil, DS: Disease severity, Inh.: disease suppression rates.*: Calculated based on stem diameter, and **: Calculated based on green shoot disease severity. *P: P value indicating the importance level.* Duncan's multiple comparison test was performed, and the difference between the treatment groups marked with the same letter was not significant at $p<0.05$. Partial η^2 values indicate the effect sizes of the main factors and interaction factors.

Table 8. PCA results regarding characters used in this study

Çizelge 8. Bu çalışmada kullanılan karakterlere ilişkin PCA sonuçları

	PCA-1	PCA-2	PCA-3	PCA-4	PCA-5	PCA-6
Eigenvalue	5.337	2.645	1.871	1.473	0.903	0.775
Variability (%)	38.125	18.896	13.364	10.523	6.448	5.539
Cumulative (%)	38.125	57.021	70.385	80.908	87.356	92.894
SL	**0.830**	0.302	-0.009	-0.342	0.122	-0.110
RL	0.349	0.293	**0.605**	-0.242	-0.093	0.483
FW	**0.603**	-0.304	0.344	0.139	0.581	-0.112
DW	**0.899**	-0.203	0.102	-0.256	0.129	0.086
SD	**0.710**	0.525	-0.156	-0.319	-0.181	0.038
LN	**0.858**	-0.031	-0.110	-0.388	0.025	-0.171
P	-0.299	-0.258	-0.676	-0.549	-0.145	**0.139**
Pht%	0.462	0.123	-0.383	**0.607**	0.135	0.450
Pht_R	-0.087	-0.187	**0.817**	-0.031	-0.402	0.032
Chl	**0.835**	-0.073	-0.150	0.183	-0.068	0.245
AMFCol	**0.758**	-0.190	0.028	0.308	-0.203	-0.402
SSD	**0.719**	-0.206	-0.193	0.359	-0.495	-0.066
DSS	-0.128	**0.958**	0.071	0.147	0.013	-0.123
DSR	-0.008	**0.970**	-0.060	0.106	0.001	-0.122

* Numbers in bold are the highest values of the attributes.

SL: Shoot Length, RL: Root Length, FW: Total Fresh Weight, DW: Total Dry Weight, SD: Shoot Diameter, LN: Leaf Number, P: Phosphorus, Pht %: Photosynt (%) Value, Pht R: Photosynt R Value, Chl: Chlorophyll, AMFCol: AMF Root Col. (%), SSD: Soil Spore Density (spores/g), DSS: Disease Scale – Shoot, DSR: Disease Scale - Root

The second component (PCA-2) accounted for 18.90% of the variance and showed the highest loadings on disease severity parameters (DSS: 0.958, DSR: 0.970), highlighting that disease-related traits constitute a distinct dimension of variation independent of growth traits (Table 8). The other components (PCA-3 to PCA-6) captured additional variability (13.36%, 10.52%, 6.45%, and 5.54%, respectively), with root length, photosynthetic R value, and phosphorus content contributing to the intermediate components. This distinction indicates that growth, physiological, and disease-related parameters are largely independent, enabling targeted interpretation of treatment effects (Table 8).

In general, PCA indicates that the most effective traits for distinguishing the effects of *F. mosseae* and essential oils under *Fusarium* stress are plant biomass and growth traits (PCA-1) and disease severity (PCA-2). These results provide a comprehensive framework for interpreting the multidimensional effects of treatments and

confirm the synergistic role of AMF and selected essential oils in enhancing growth while alleviating disease.

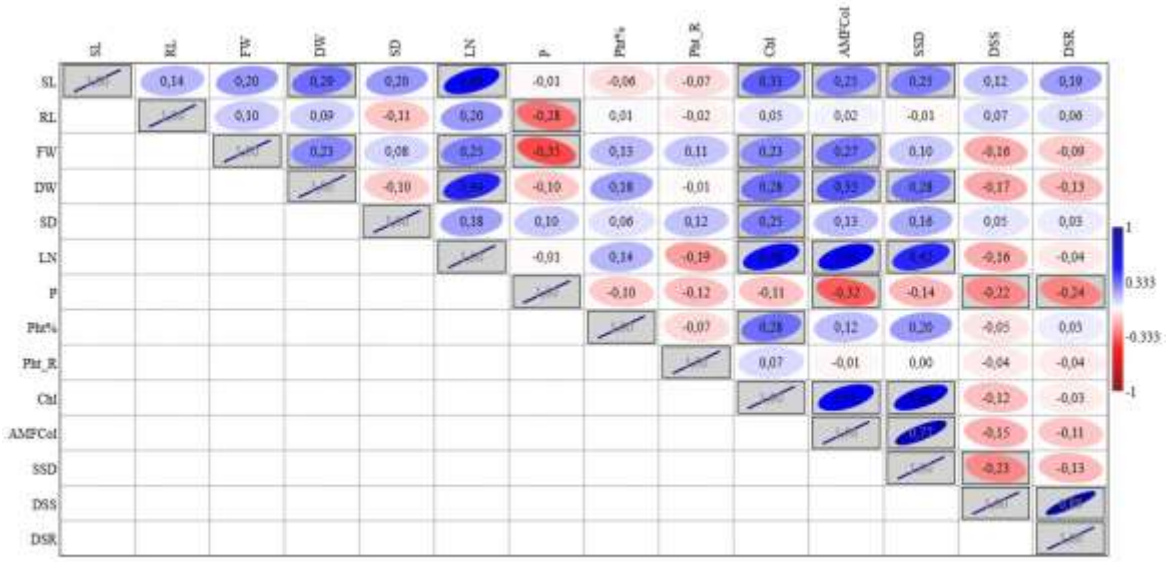

Figure 1. Pearson correlation coefficients between features.
Values in bold frame are different from 0, and the significance level is alpha: 0.05. SL: Shoot Length, RL: Root Length, FW: Total Fresh Weight, DW: Total Dry Weight, SD: Shoot Diameter, LN: Leaf Number, P: Phosphorus, Pht %: Photosynt (%) Value, Pht R: Photosynt R Value, Chl: Chlorophyll, AMFCol: AMF Root Col. (%), SSD: Soil Spore Density (spores/g), DSS: Disease Scale – Shoot, DSR: Disease Scale- Root

Şekil 1. Özellikler arasındaki Pearson korelasyon katsayıları.
Kalın çerçeve içindeki değerler 0'dan farklıdır ve anlamlılık düzeyi alfa: 0,05'tir. SL: Sürgün Uzunluğu, RL: Kök Uzunluğu, FW: Toplam Taze Ağırlık, DW: Toplam Kuru Ağırlık, SD: Sürgün Çapı, LN: Yaprak Sayısı, P: Fosfor, Pht %: Fotosent (%) Değeri, Pht R: Fotosent R Değeri, Chl: Klorofil, AMFCol: AMF Kök Rengi (%), SSD: Toprak Spor Yoğunluğu (spor/g), DSS: Hastalık Ölçeği – Sürgün, DSR: Hastalık Ölçeği – Kök

Figure 1 shows the Pearson correlation coefficients between measured plant growth, physiological, and disease-related traits. Values highlighted in bold indicate statistically significant correlations at the $\alpha = 0.05$ level and demonstrate meaningful relationships between variables.

The analysis reveals a strong positive correlation between shoot length (SL), leaf number (LN), and total dry weight (DW). This indicates that plants with longer shoots tend to develop more leaves and accumulate higher biomass. Similarly, chlorophyll content (Chl) is positively related to SL and DW. This indicates that increased photosynthetic capacity is associated with improved growth performance (Figure 1).

Conversely, disease severity parameters (DSS, DSR) show a negative correlation with growth traits, confirming that higher disease pressure reduces plant development and biomass accumulation. AMF root colonization (AMFCol) also shows a positive correlation with growth parameters and a negative correlation with disease severity, supporting the protective role of *F. mosseae* in alleviating *Fusarium*-induced stress (Figure 1).

Overall, these correlations provide quantitative evidence of the interaction between plant growth, physiological performance, mycorrhizal colonization, and disease severity, highlighting the key properties that respond synergistically to the combined application of *F. mosseae* and essential oils.

Figure 2 shows the PCA loading plot for the first two principal components (PCA-1 and PCA-2) and illustrates how individual traits contribute to the variation observed between treatments. PCA-1, which explains 38.13% of the total variance, is dominated by biomass traits such as plant growth and shoot length (SL), leaf number (LN), dry weight (DW), and chlorophyll content (Chl). These traits are clustered closely together, indicating a strong relationship among growth-related variables.

PCA-2, which explains 18.90% of the variance, is primarily associated with disease severity parameters (DSS, DSR) that are nearly orthogonal to growth traits. This distinction highlights that disease response constitutes a distinct axis of variation largely independent of growth and physiological traits (Figure 2).

The loading diagram clearly shows that the characteristics are grouped. This indicates that *F. mosseae* inoculation

and essential oil applications affect plant growth and disease responses through separate but complementary mechanisms. Overall, this figure visually represents the multidimensional effects of the treatments and highlights the contrasting contributions of growth and disease traits in differentiating the experimental results (Figure 2).

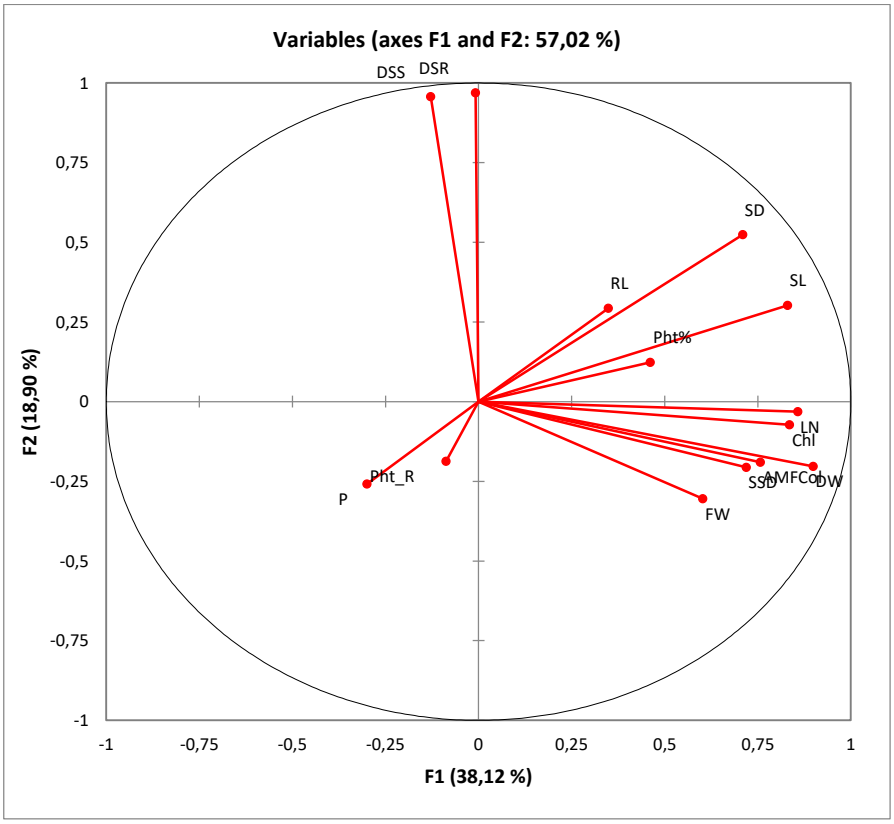

Figure 2. Character-based PCA loading plot for the first two major components
Şekil 2. İlk iki ana bileşen için karakter tabanlı PCA yükleme grafiği

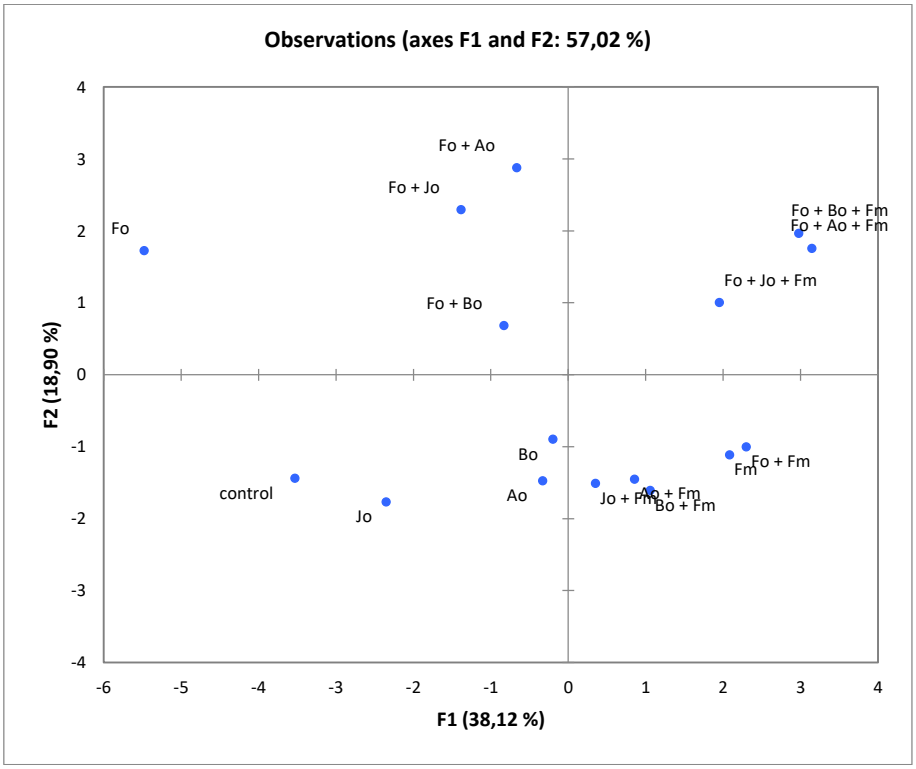

Figure 3. The score plot for the PCA analysis's initial two principal components
Şekil 3. PCA analizinin ilk iki ana bileşenini gösteren puan grafiği

Figure 3 shows the score plot of the first two principal components (PCA-1 and PCA-2) and displays the distribution of treatments according to their multivariate characteristics. Treatments are positioned according to the combined effects of plant growth, physiological, and disease-related characteristics, thus enabling a visual comparison of their overall responses.

The graph shows that treatments using *F. mosseae* alone or in combination with effective essential oils (e.g., Fo+Fm, Fo+Bo+Fm) form a distinct group compared to treatments using only the pathogen (Fo) or less effective combinations (Fo+Ao). Along PCA-1, this distinction reflects differences in growth and biomass traits, while along PCA-2, this distinction corresponds to responses to disease severity (Figure 3).

In general, the score plot visually reinforces the synergistic effects of AMF and essential oils under *Fusarium* stress, confirming that *F. mosseae* and compatible essential oil treatments produce different physiological and disease alleviation profiles. This visualization complements the PCA loading graph (Figure 2) by showing how treatments are grouped according to their multivariate performance.

DISCUSSION

This study demonstrated that black seed, juniper, and argan oils, used alone or in combination, and *F. mosseae*, have distinct effects on inhibiting *F. oxysporum* in pepper plants. The data indicate that essential oil efficacy, particularly at 3%, varies by type, with juniper and black seed oils being most effective, while argan oil had a moderate effect. These findings emphasize the powerful protective role of *F. mosseae* alone, but also reveal that its interaction with essential oils does not show a uniform synergistic effect; rather, it is complex and, in some specific cases, even antagonistic. A likely mechanistic explanation for the positive effect of argan and juniper oils is that their volatile terpenoid and phenolic profiles do not block the AMF signal or membrane changes. This allows mutual nutrient transfer to continue without interference. In contrast, the main bioactive compounds in black seed oil may change root surface chemistry, membrane permeability, or microbial processes. This can disrupt the coordination between AMF hyphae and host cells (Abbas et al., 2024). This shows that specific essential oil molecules can protect, boost, or disrupt AMF-supported defense pathways. Table 3 shows that the Fm treatment significantly increased the fresh weight, dry weight, root length, and shoot length. For example, in the Fo+Fm treatment, the fresh weight was 26.45 g, and the dry weight was 4.08 g. Root colonization peaked at 89% in Fo+Fm, demonstrating a strong symbiotic effect (Table 6). These results are consistent with the research conducted by Soussani et al. (2025), which demonstrated that mycorrhizal inoculation increases plant biomass and physiological resilience in sweet peppers. Previous studies conducted by Qian et al. (2015) have shown that *F. mosseae* increases plant growth by reducing the amount of pathogen DNA that causes soybean root rot. The results of this study, which show that Fm increases morpho-biomass parameters, are consistent with findings in the literature.

While Fo infection caused a decrease in shoot diameter, leaf number, and phosphorus, Fm application resulted in the maximum leaf number. In addition, some essential oils, such as Bo, showed more effective performance than the phosphorus control (Table 4). Moutassem et al. (2019) reported that various essential oils found in chickpea plants trigger systemic resistance, with disease-suppressing effects occurring rapidly, up to 99%. Ahmed and Shehata (2023) demonstrated the positive effects of different aromatic oil plants on phosphorus uptake and leaf development in *F. oxysporum*. Da Silva et al. (2014) noted that the components of *Piper divaricatum* oil exhibit strong antifungal effects against *Fusarium* species and that this effect is closely related to leaf chlorophyll measurements, such as SPAD. These studies support this findings in Table 4 regarding changes in leaf and phosphorus levels in the literature (Table 4). There were significant differences in phosphorus uptake between treatments (Table 6). Considering that AMF generally increases P uptake by increasing the root absorption area (Mai et al., 2018), it was surprising that the Fo+Fm combination had the lowest P content. This decrease was likely due to root damage caused by *F. oxysporum* and the disruption of AMF structures necessary for P transport (Andrino et al., 2021). Wahab et al. (2023) demonstrated similar antagonistic effects of pathogens on AMF-mediated nutrient uptake and suggested that biotic stress can significantly reduce the efficiency of mycorrhizal phosphorus transfer.

In this study, a significant increase in chlorophyll content (measured by SPAD) was observed in triple combinations (Table 5). According to the SPAD data, the chlorophyll concentration increased significantly in combination with Fm (Fo+Ao+Fm, Fo+Bo+Fm) (Table 4). Triple combinations made with FM and essential oils significantly increased chlorophyll content and enhanced nutrient uptake, thereby supporting increased photosynthetic efficiency (Table 5). These findings suggest that the use of mycorrhizal treatments in combination with certain oils may not only support pigment synthesis but also increase physiological resistance (Bona et al. 2016). AMF applications increase the photosynthetic efficiency and chlorophyll content, as shown by Abdel Latef & Miransari (2014). Similarly, Umer (2025) noted that combining AMF with other biological agents increases plant photosynthetic efficiency. Together, these findings help explain the increase in SPAD and improvements in

photophysiology, as shown in Table 4.

The study found that the effects of biological agents are interactive and dose-dependent, influencing mycorrhizal colonization, disease suppression, and plant dependency on mycorrhiza. *F. mosseae* application uniquely increased soil spore density, dependency, and root colonization, confirming its role in enhancing tolerance to pathogenic stress. Application of oils, particularly juniper, reduced mycorrhizal dependency, likely due to certain bioactive compounds that inhibited both pathogenic and beneficial fungi. Nonetheless, even under these antagonistic effects, some oil and *F. mosseae* combinations (e.g., Fo+Bo+Fm) maintained moderate disease suppression, underscoring the partial but persistent protective capacity of mycorrhizal fungi.

These findings suggest that fungal–plant symbioses can be adversely influenced by bioactive phenolic constituents of plant-derived oils. Tarraf et al. (2015) similarly emphasized that essential oils have antifungal properties against certain mycorrhizal species. In particular, the ability of black seed oil to reduce colonization by 43.75% suggests that these substances may interfere with mutualistic symbiotic relationships (Table 5). According to Wang et al. (2022), AM colonization activates defense genes and triggers the JA signalling pathway. However, another interesting finding is that the disease suppression efficacy decreases when essential oils and mycorrhizal fungi are used together. In particular, compared with mycorrhizal treatments alone, disease severity was greater for the Fo+Ao+Fm (2.20%) and Fo+Bo+Fm (2.60%) combinations (Table 5). These findings suggest that essential oils may inhibit symbiotic fungi, thereby reducing their biological control capacity. According to Al Raish et al. (2025), if the agents are chemically incompatible, the symbiotic balance may be disrupted in such combination applications.

The Fo+Fm application had the lowest disease severity parameter value (0.60%) (Table 6). This implies *that F. mosseae* prevents pathogen colonization by providing a competitive advantage in the soil. According to Singh (2019), AMFs can effectively combat soil-borne diseases, including *Fusarium* spp., by triggering induced systemic resistance mechanisms. However, only essential oil application, particularly at a 3% concentration, reduced the severity of the condition to some extent (e.g., Fo+Bo 1.20%) (Table 6). According to Mohammed et al. (2019), these findings suggest that the antibacterial properties of black seed oil may help plants defend themselves. According to De Lamo and Takken (2020), the Fm application results in phenotypic suppression by inhibiting genes that control the cell wall components of the pathogen *F. oxysporum*.

In general, the combination of *F. mosseae* with selected essential oils provided a synergistic defense that increased growth, physiological performance, and suppression of *Fusarium* in pepper plants.

CONCLUSION

This study revealed that pepper plants exposed to *F. oxysporum* disease stress can benefit from the morphological and physiological effects of the mycorrhizal fungi *F. mosseae*. By promoting plant growth, increased mycorrhizal colonization significantly reduces disease pressure and supports sustainable agricultural practices. The ability of essential oils to suppress disease varies depending on their type and concentration; some oils have been found to have negative effects on mycorrhizal symbiosis, thereby reducing the effectiveness of biological control. In this study, it was observed that certain essential oils did not exhibit the expected synergistic effect when applied together with *F. mosseae* and could even sometimes lead to antagonistic interactions.

These results highlight the importance of choosing and using biological agents effectively. This approach maximizes their effectiveness. Sustainable agriculture depends largely on mycorrhizal fungi, which improve plant resilience and soil health. However, experiences with essential oils show that combining them with other biological agents may not always yield good results. Mycorrhizal fungi should therefore be prioritized in integrated disease control. The effects of essential oils should be assessed by species. Future research should use controlled greenhouse conditions to fully clarify the interactions and effects of oils and mycorrhiza. This strategy balances sustainability and productivity and increases the effectiveness of biological control in agriculture.

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Ethical Approval

No ethical committee approval is required as no humans or animals were used in the research.

Contribution Rate Statement Summary of Researchers

The authors declare that they have contributed equally to the article.

Conflict of Interest

The authors declare that there is no conflict of interest between them.

REFERENCES

Abbas, M., Gururani, M. A., Ali, A., Bajwa, S., Hassan, R., Batool, S. W., ... & Wei, D. (2024). Antimicrobial properties and therapeutic potential of bioactive compounds in Nigella sativa: A review. *Molecules, 29*(20), 4914. https://doi.org/10.3390/molecules29204914

Abdel Latef, A.A.H., & Miransari, M. (2014). *The role of arbuscular mycorrhizal fungi in alleviation of salt stress*. In: Use of Microbes for the Alleviation of Soil Stresses: Volume 2: Alleviation of Soil Stress by PGPR and Mycorrhizal Fungi, Springer, New York, NY, pp. 23–38. https://doi.org/10.1007/978-1-4939-0721-2_2

Abkenar, M.B., Mozafari, H., Karimzadeh, K., Rajabzadeh, F., & Azimi, R. (2024). Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) as an alternative to mineral fertilizers to improve the growth, essential oil profile, and phenolic content of *Satureja macrantha* L. *Journal of Crop Health, 76*, 347–356. https://doi.org/10.1007/s10343-023-00934-0

Ahmad, A., Sripong, K., Uthairatanakij, A., Photchanachai, S., Pankasemsuk, T., & Jitareerat, P. (2022). Decontamination of seed-borne disease in pepper (*Capsicum annuum* L.) seed and the enhancement of seed quality by the emulated plasma technology. *Scientia Horticulturae*, *291*, 110568. https://doi.org/10.1016/j.scienta.2021.110568

Ahmad, N., Abbas, A., Shamsullah, S., Jabran, M., & Ali, M.A. (2023). *Fusarium* wilt disease of chili: pathogen, its mechanism of infection, eradication, and impacts. *Phytopathogenom. Dis. Control, 2*, 95–110. https://doi.org/10.22194/Pdc/2.1024

Ahmed, A.F. & Shehata, A.M. (2023). Improving growth, yield, and oil productivity of rosemary plants grown in sandy calcareous soil by using some manures organic tea and salicylic acid. *International Journal of Plant Production, 14*, 479–487. 10.21608/jpp.2023.234844.1269

Alaoui, M.M. (2020). Antifungal effect of natural extracts on fungal contamination in the vitro culture of *Calodendrum capense* (Lf.) Thunberg. *Journal of Materials and Environmental Science,11*, 647–657.

Al Raish, S.M., Sourani, O.M., & Abu-Elsaoud, A.M. (2025). Plant growth-promoting microorganisms as biocontrol agents: Mechanisms, challenges, and future prospects. *Applied Microbiology, 5*(2), 44.. https://doi.org/10.3390/applmicrobiol5020044

Amani Machiani, M., Javanmard, A., Ostadi, A., & Alizadeh, K. (2023). Improvement in essential oil quantity and quality of thyme (*Thymus vulgaris* L.) by integrative application of chitosan nanoparticles and arbuscular mycorrhizal fungi under water stress conditions. *Plants, 12*(7), 1422... https://doi.org/10.3390/plants12071422

Andrino, A., Guggenberger, G., Kernchen, S., Mikutta, R., Sauheitl, L., & Boy, J. (2021). Production of organic acids by arbuscular mycorrhizal fungi and their contribution in the mobilization of phosphorus bound to iron oxides. *Frontiers in Plant Science*, *12*, 661842. https://doi.org/10.3389/fpls.2021.661842

Atay, M., & Soylu, S. (2023). Kurutmalık Biber meyvelerinde iç çürüklüğüne neden olan fungal etmenlere karşı bitki uçucu yağlarının *in vitro* antifungal etkileri. *KSU Tarım ve Doğa Dergisi, 26*(1), 76-89. https://doi.org/10.18016/ksutarimdoga.vi.1085859

Basaid, K., & Furze, J.N. (2024). Botanical-microbial synergy—fundamentals of untapped potential of sustainable agriculture. *Journal of Crop Health, 76*, 1263–1280. https://doi.org/10.1007/s10343-024-01008-5

Begum, N., Qin, C., Ahanger, M.A., Raza, S., Khan, M.I., Ashraf, M., & Zhang, L. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. *Frontiers in Plant Science*,*10*, 1068. https://doi.org/10.3389/fpls.2019.01068

Bona, E., Lingua, G., & Todeschini, V. (2016). *Effect of bioinoculants on the quality of crops*. In: *Bioformulations: for Sustainable Agriculture*, Springer, New Delhi, pp. 93–124. https://doi.org/10.1007/978-81-322-2779-3_5

Cerkauskas, R.F. (2017). Etiology and management of *Fusarium* crown and root rot (*Fusarium oxysporum*) on greenhouse pepper in Ontario, Canada. *Can. J. Plant Pathol. 39*(2), 121–132. https://doi.org/10.1080/07060661.2017.1321044

Da Silva, J.K.R., Silva, J.R.A., Nascimento, S.B., Da Luz, S.F., Meireles, E.N., Alves, C.N., & Maia, J.G.S. (2014). Antifungal activity and computational study of constituents from *Piper divaricatum* essential oil against *Fusarium* infection in black pepper. *Molecules, 19(11)*, 17926–17942. https://doi.org/10.3390/molecules191117926

Declerck, S., Plenchette, C., & Strullu, D.G. (1995). Mycorrhizal dependency of banana (Musa acuminate, AAA group) cultivar. *Plant Soil, 176*, 183–187. https://doi.org/10.1007/BF00017688

De Lamo, F.J., & Takken, F.L. (2020). Biocontrol by *Fusarium oxysporum* using endophyte-mediated resistance. Front. *Plant Science, 11*, 37. https://doi.org/10.3389/fpls.2020.00037

Frans, M., Aerts, R., Van Laethem, S., & Ceusters, J. (2017). Environmental effects on growth and sporulation of

Fusarium spp. Causing internal fruit rot in bell pepper. *European Journal of Plant Pathology, 149*, 875–883. https://doi.org/10.1007/s10658-017-1235-4

Gerdemann, L.W., & Nicholson, T.H. (1963). Spores of mycorrhizal endogene extracted from soil by wet sieving and decanting. *Transactions of the British Mycological Society,46*, 235–244.

Giovanetti, M., & Mosse, B. (1980). An evaluation of techniques for measuring vesicular-arbuscular mycorrhizal infection in roots. *New Phytologist,84*, 489–500. https://www.jstor.org/stable/2432123

Güneş, H., Demir, S., Durak, E.D., & Boyno, G. (2024). The effect of arbuscular mycorrhizal fungal species *Funneliformis mosseae* and biochar against *Verticillium dahliae* in pepper plants under salt stress. *European Journal of Plant Pathology, 170*, 669–686. https://doi.org/10.1007/s10658-024-02926-w

Greff, B., Sáhó, A., Lakatos, E., & Varga, L. (2023). Biocontrol activity of aromatic and medicinal plants and their bioactive components against soil-borne pathogens. *Plants 12*(4), 706. https://doi.org/10.3390/plants12040706

Gruľová, D., Baranová, B., Sedlák, V., De Martino, L., Zheljazkov, V. D., Konečná, M., ... & De Feo, V. (2022). Juniperus horizontalis Moench: Chemical composition, herbicidal and insecticidal activities of its essential oil and of its main component, sabinene. Molecules, 27(23), 8408.

Hashem, A., Almutairi, K.F., Alshaikh, N.A., Kumar, A., Wu, Q.S., Ibramimova, U., & Abd-Allah, E.F. (2025). *Role of arbuscular mycorrhizal fungi in plant growth promotion and biotic stress management*. In: Management of Mycorrhizal Symbiosis for Mycoremediation and Phytostabilization. Elsevier, pp. 145–155. https://doi.org/10.1016/B978-0-443-24863-4.00008-X

Hegazy, M.M., Mekky, R.H., Ibrahim, A.E., Abouelela, M.E., Kedra, T.A., & Al-Harrasi, A. (2025). Essential Oils: The Science of Extraction and Its Implications for Composition and Biological Activity—A Review. *Food Analytical Methods 18*, 1483-1513. https://doi.org/10.1007/s12161-025-02808-9

Jojić, A. A., Liga, S., Uțu, D., Ruse, G., Suciu, L., Motoc, A., ... & Tchiakpe-Antal, D. S. (2024). Beyond Essential Oils: Diterpenes, Lignans, and Biflavonoids from Juniperus communis L. as a Source of Multi-Target Lead Compounds. *Plants, 13*(22), 3233.

Kamal, R., Gusain, Y.S., Kumar, V., & Sharma, A.K. (2015). Disease management through biological control agents: An eco-friendly and cost-effective approach for sustainable agriculture—A Review. *Agricultural Reviews 36*(1), 37–45. 10.5958/0976-0741.2015.00004.5

Khaitov, B., Umurzokov, M., Cho, K.M., Lee, Y.J., Park, K.W., & Sung, J. (2019). Importance and production of chilli pepper; heat tolerance and efficient nutrient use under climate change conditions. *Korean Journal of Agricultural Science 46*(4), 769–779. https://doi.org/10.7744/kjoas.20190059

Kim, B.S., & Hwang, B.K. (2007). Microbial fungicides in the control of plant diseases. *Journal of Phytopathology 155*(11–12), 641–653. https://doi.org/10.1111/j.1439-0434.2007.01314.x

Li, N., Wang, C., Li, X., & Liu, M. (2019). Effects of earthworms and arbuscular mycorrhizal fungi on preventing Fusarium oxysporum infection in the strawberry plant. *Plant and Soil, 443*(1), 139-153.

Lorito, M., Peterbauer, C., Hayes, C.K., & Harman, G.E. (1994). Synergistic interaction between fungal cell wall-degrading enzymes and different antifungal compounds enhances inhibition of spore germination. *Microbiology 140*(3), 623–629. https://doi.org/10.1099/00221287-140-3-623

Mai, W., Xue, X., Feng, G., & Tian, C. (2018). Simultaneously maximizing root/mycorrhizal growth and phosphorus uptake by cotton plants by optimizing water and phosphorus management. *BMC Plant Biology*, *18*(1), 334. https://doi.org/10.1186/s12870-018-1550-8

Manjunath, M.S., Koshariya, A.K., Sharma, N., Rajput, A., Pandey, S.K., Singh, S., & Singh, B.V. (2023). Exploring the use of aromatic compounds in crop growth and protection. *International Journal of Plant & Soil Science,35*(21), 78–89. 10.9734/IJPSS/2023/v35i213948

McGuire, R.G. (1992). Reporting of objective color measurements. *HortScience 27*, 1254–1255.

Mohammed, S. J., Amin, H. H., Aziz, S. B., Sha, A. M., Hassan, S., Abdul Aziz, J. M., & Rahman, H. S. (2019). Structural characterization, antimicrobial activity, and *in vitro* cytotoxicity effect of black seed oil. *Evidence-Based Complementary and Alternative Medicine, 2019*(1), 6515671. https://doi.org/10.1155/2019/6515671

Moumou, M., Mokhtari, I., Tayebi, A., Milenkovic, D., Amrani, S., & Harnafi, H. (2024). Juniperus oxycedrus L. fruit, leaves, and essential oil: a systematic literature review on bioactive compounds, pharmacological properties, and toxicology. *Phytochemistry Reviews,* 1–31. https://doi.org/10.1007/s11101-024-10054-w

Moutassem, D., Belabid, L., Bellik, Y., Ziouche, S., & Baali, F. (2019). Efficacy of essential oils of various aromatic plants in the biocontrol of *Fusarium* wilt and inducing systemic resistance in chickpea seedlings. *Plant Protection Science 55*(3). 10.17221/134/2018-PPS

Ninkuu, V., Zhang, L., Yan, J., Fu, Z., Yang, T., Zeng, H. (2021). Biochemistry of terpenes and recent advances in plant protection. *International Journal of Molecular Sciences 22*(11), 5710. https://doi.org/10.3390/ijms22115710

Qian, L., Yu, W.J., Cui, J.Q., Jie, W.G., & Cai, B.Y. (2015). *Funneliformis mosseae* affects the root rot pathogen *Fusarium oxysporum* in soybeans. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science 65*(4), 321–

328. https://doi.org/10.1080/09064710.2015.1009938

Rasouli, F., Nasiri, Y., Hassanpouraghdam, M.B., Asadi, M., Qaderi, T., Trifa, A., & Szczepanek, M. (2023). Seaweed extract and arbuscular mycorrhiza co-application affect the growth responses and essential oil composition of *Foeniculum vulgare* L. *Scientific Reports 13*(1), 11902. https://doi.org/10.1038/s41598-023-39194-3

Rasul, S.Z.R. (2019). *Biocontrol of Trichoderma spp. and Saccharomyces cerevisiae against Fusarium oxysporum f.sp. Lycopersici in tomato*. Master's Thesis. Van Yuzuncu Yil University, Institute of Science, Van.

Raveau, R., Fontaine, J., & Lounès-Hadj Sahraoui, A. (2020). Essential oils as potential alternative biocontrol products against plant pathogens and weeds: A review. *Foods 9*(3), 365. https://doi.org/10.3390/foods9030365

Rydlová, J., Jelínková, M., Dušek, K., Dušková, E., Vosátka, M., & Püschel, D. (2016). Arbuscular mycorrhiza differentially affects the synthesis of essential oils in coriander and dill. *Mycorrhiza, 26*(2), 123-131.

Schüßler, A., & Walker, C. (2010). *The Glomeromycota: a species list with new families and new genera*. The Royal Botanic Garden Kew, Botanische Staatssammlung Munich, and Oregon State University.

Shoresh, M., Harman, G.E., & Mastouri, F. (2010). Induced systemic resistance and plant responses to fungal biocontrol agents. *Annual Review of Phytopathology 48*(1), 21–43. https://doi.org/10.1146/annurev-phyto-073009-114450

Singh, V., Naveenkumar, R., & Muthukumar, A. (2019). Arbuscular mycorrhizal fungi and their effectiveness against soil borne diseases. *Management 183*, 199.

Soussani, F.E., Nilahyane, A., Ikan, C., Ouhaddou, R., Ben-Laouane, R., Salah-Eddine, H., & Meddich, A. (2025). Enhancing sweet pepper tolerance to combined drought and salinity stresses: synergistic role of biochar and arbuscular mycorrhizal fungi. *Journal of Crop Health 77*(2), 1–17. https://doi.org/10.1007/s10343-025-01145-5

Soylu, E. M., Kurt, Ş., & Soylu, S. (2010). *In vitro* and *in vivo* antifungal activities of the essential oils of various plants against tomato grey mould disease agent *Botrytis cinerea*. *International Journal of Food Microbiology, 143*(3), 183-189. https://doi.org/10.1016/j.ijfoodmicro.2010.08.015

Soylu, S., Atay, M., Kara, M., Uysal, A., Soylu, E. M., & Kurt, Ş. (2023). Morphological and molecular characterization of *Fusarium incarnatum* as a causal disease agent of pepper (*Capsicum annuum*) fruit rot. *Journal of Phytopathology, 171*(11-12), 688-699. https://doi.org/10.1111/jph.13228

Tabassum, N., & Vidyasagar, G.M. (2013). Antifungal investigations on plant essential oils. A review. *International Journal of Pharmacy and Pharmaceutical Sciences 5*(2), 19–28.

Tarraf, W., Ruta, C., De Cillis, F., Tagarelli, A., Tedone, L., & De Mastro, G. (2015). Effects of mycorrhiza on growth and essential oil production in selected aromatic plants. *Italian Journal of Agronomy 10*(3), 633. https://doi.org/10.4081/ija.2015.633

Umer, M., Anwar, N., Mubeen, M., Li, Y., Ali, A., Alshaharni, M.O., & Liu, P. (2025). Roles of arbuscular mycorrhizal fungi in plant growth and disease management for sustainable agriculture. *Frontiers in Microbiology 16*, 1616273. https://doi.org/10.3389/fmicb.2025.1616273

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., & Reddy, S.P.P. (2023). Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants 12*(17), 3102. https://doi.org/10.3390/plants12173102

Wang, H., Hao, Z., Zhang, X., Xie, W., & Chen, B. (2022). Arbuscular mycorrhizal fungi induced plant resistance against *Fusarium* wilt in jasmonate biosynthesis defective mutant and wild type of tomato. *Journal of Fungi 8*(5), 422. https://doi.org/10.3390/jof8050422