

## Antifungal Potential of *Salvia officinalis* L. in the Control of Phytopathogens Associated with Strawberry Crops: A State-of-the-Art Review

### Potencial antifúngico de *Salvia officinalis* L. en el control de fitopatógenos asociados al cultivo de fresa: una revisión del estado del arte

Alejandra Medina-Peralta<sup>a</sup>, Marycarmen Cortes-Hernández<sup>a,c</sup>, Laura Afanador-Barajas<sup>b</sup>, Sergio R. Pérez-Ríos<sup>a</sup>, Gabriela Medina-Pérez<sup>a</sup>, Paola M. Mendoza-Martínez<sup>a\*</sup>

---

#### \*Abstract:

Fungal diseases are among the main limiting factors affecting the production of high-value crops such as strawberry (*Fragaria × ananassa*). The intensive use of synthetic fungicides has led to microbial resistance, environmental contamination, and risks to human health, prompting the search for sustainable alternatives. Plant extracts, particularly those derived from *Salvia officinalis* L., have gained attention due to their rich content of bioactive secondary metabolites with antimicrobial properties. This narrative (non-systematic) review examines the current state of knowledge on the antifungal activity of *S. officinalis*, focusing on its phytochemical composition, mechanisms of action, extraction methods, and experimental evidence against relevant phytopathogenic fungi, including *Botrytis cinerea* and *Colletotrichum acutatum*. The literature reports inhibitory effects under experimental conditions, primarily attributed to phenolic compounds, terpenoids, and flavonoids, which disrupt fungal cell membranes and metabolic processes. This review highlights the potential of *S. officinalis* as a sustainable alternative for phytosanitary management in strawberry production systems.

#### Keywords:

*Salvia officinalis*; strawberry (*Fragaria × ananassa*); phytopathogenic fungi; antifungal activity; plant extracts; biofungicides; secondary metabolites; postharvest diseases; sustainable agriculture.

---

#### Resumen:

Las enfermedades causadas por hongos fitopatógenos representan uno de los principales factores limitantes de la producción de cultivos de alto valor económico, como la fresa (*Fragaria × ananassa*). El uso intensivo de fungicidas sintéticos ha generado problemas asociados a la resistencia microbiana, impactos ambientales y riesgos para la salud humana, lo que ha impulsado la búsqueda de alternativas más sostenibles. En este contexto, los extractos vegetales, en particular los derivados de *Salvia officinalis* L., han sido ampliamente estudiados por su contenido de metabolitos secundarios con propiedades antimicrobianas. El presente artículo de revisión narrativa analiza el estado del arte sobre la actividad antifúngica de *S. officinalis*, considerando su composición fitoquímica, mecanismos de acción, métodos de extracción y evidencia experimental frente a hongos fitopatógenos de importancia agrícola, como *Botrytis cinerea* y *Colletotrichum acutatum*. La literatura revisada indica que los extractos de salvia presentan actividad inhibitoria en condiciones experimentales, atribuida principalmente a compuestos fenólicos, terpenoides y flavonoides, que afectan la integridad de la membrana celular fúngica y los procesos metabólicos esenciales. Este análisis destaca el potencial de *S. officinalis* como alternativa sostenible para el manejo fitosanitario del cultivo de fresa.

**Palabras Clave:** *Salvia officinalis*; fresa (*Fragaria × ananassa*); hongos fitopatógenos; actividad antifúngica; extractos vegetales; biofungicidas; metabolitos secundarios; enfermedades postcosecha; agricultura sustentable.

---

<sup>a</sup> Universidad Autónoma del Estado de Hidalgo; | [me382233@uaeh.edu.mx](mailto:me382233@uaeh.edu.mx), <https://orcid.org/0009-0005-4456-8786>; [sperez@uaeh.edu.mx](mailto:sperez@uaeh.edu.mx), <https://orcid.org/0000-0001-7892-4842>; [gabriela\\_medina@uaeh.edu.mx](mailto:gabriela_medina@uaeh.edu.mx), <https://orcid.org/0000-0001-8673-941X>; [me439957@uaeh.edu.mx](mailto:me439957@uaeh.edu.mx), <https://orcid.org/0009-0007-4483-3994>.

<sup>b</sup> Investigadora Posdoc DGAPA, Departamento de Microbiología Molecular, Instituto de Biotecnología, Universidad Nacional Autónoma de México (UNAM), <https://orcid.org/0000-0002-8133-7048>, [laura.afanador@gmail.com](mailto:laura.afanador@gmail.com)

<sup>c</sup> Center for Research and Advanced Studies of the National Polytechnic Institute, Coahuila; <https://orcid.org/0000-0002-8508-0366>, [marycarmencohdz@cinvestav.mx](mailto:marycarmencohdz@cinvestav.mx)

\*autor de correspondencia

Fecha de recepción: 20/03/2026, Fecha de aceptación: 18/04/2026, Fecha de publicación: 05/07/2026

DOI: <https://doi.org/10.29057/icap.v12i24.17567>



## 1. Introduction

Strawberry (*Fragaria spp.*) is a valuable and important food crop, and its fruit is highly appreciated by consumers worldwide. In addition to its nutritional value and sensory attributes, such as texture, color, flavor, and aroma, strawberries provide significant health benefits. This is due to the presence of bioactive compounds with various functions, including glycemic control, high antioxidant capacity, and potential cancer-preventive effects. [1, 2]. However, this crop is susceptible to diseases caused by *Colletotrichum acutatum*. This pathogen causes anthracnose in strawberries, resulting in severe crop damage; it also affects other crops, albeit to a lesser extent, such as blueberries, apples, and avocados. The fungus may develop symptoms rapidly or remain quiescent until the postharvest stage. [3, 4].

Currently, the primary method of control relies on fungicides; however, their excessive use can cause physiological damage to plants and negatively impact on the environment and human health. For this reason, efforts have focused on identifying natural, environmentally friendly alternatives to protect crops. [5]. One such alternative is the use of plant extracts as biofungicides, owing to their secondary metabolite content. [6]. These compounds can be classified according to their biosynthetic pathways into three main groups: terpenoids, nitrogen-containing metabolites, and phenolic compounds. The latter play an important role in plant growth and reproduction, primarily serving to protect plants against pathogens, predators, and other stressors such as ultraviolet radiation. [7].

An interesting source of plant extracts is *Salvia officinalis* L., a perennial herbaceous plant in the Lamiaceae family, commonly found in Mediterranean regions and other temperate areas worldwide. Its leaves contain diterpenes and phenolic compounds with antibacterial, antifungal, and antiviral properties. [8]

## 2. Methodological Approach

This study was conducted as a narrative review (state-of-the-art) to synthesize and critically analyze current scientific knowledge on the antifungal

potential of *Salvia officinalis* L. against phytopathogenic fungi associated with strawberry (*Fragaria × ananassa*) crops.

### 2.1. Literature Search Strategy

A comprehensive, non-systematic literature search was conducted using major scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. The search focused on identifying relevant peer-reviewed articles, reviews, and scientific reports addressing the antifungal properties of *S. officinalis* and its application in plant disease management. The search was guided by a combination of keywords such as: “*Salvia officinalis*”, “antifungal activity”, “plant extracts”, “phytopathogenic fungi”, “*Botrytis cinerea*”, “*Colletotrichum spp.*”, “biofungicides”, and “postharvest diseases”. The inclusion of references was guided by the following criteria: Scientific relevance to the antifungal activity of *Salvia officinalis*, contribution to understanding phytochemical composition or mechanisms of action, applicability to phytopathogenic fungi, particularly those affecting strawberry crops, and inclusion of both foundational and recent studies (with emphasis on publications from 2015 to 2025). No rigid exclusion protocol was applied; however, non-scientific sources and studies lacking methodological clarity were avoided whenever possible.

### 2.2 Scope and Limitations

As a narrative review, this study does not aim to provide an exhaustive or statistically structured synthesis of all available evidence. Instead, it offers a critical and integrative perspective on the topic. Limitations include variability in experimental conditions across studies, differences in extraction methods, and the predominance of in vitro assays, which may limit direct extrapolation to field conditions.

## 3. Phytopathogenic Fungi in Strawberry Crops

Fungal pathogens are among the most significant constraints on strawberry (*Fragaria × ananassa*) production worldwide, affecting yield, fruit quality, and postharvest shelf life [9]. These microorganisms are considered the most economically important group of pathogens in strawberry cultivation because they

infect all plant tissues, including roots, crowns, leaves, flowers, and fruits. The susceptibility of strawberry plants to fungal infections, combined with favorable environmental conditions such as high humidity and moderate temperatures, creates an ideal scenario for disease development and rapid pathogen dissemination.

Among the most relevant fungal pathogens in strawberry crops are *Botrytis cinerea* and *Colletotrichum* spp. stand out as the primary causal agents of gray mold and anthracnose, respectively [3, 10]. *Botrytis cinerea* is a necrotrophic fungus that infects more than 1,400 plant species and is considered one of the most destructive pathogens in horticultural systems. [11]. In strawberries, it causes gray mold disease, which can lead to yield losses of 25–55% preharvest and 80–89% during postharvest storage, making it a major contributor to global economic losses. [9]. This pathogen primarily infects flowers and fruits, often initiating infections in senescent floral tissues that later colonize developing fruits. Its ability to remain latent and continue development under refrigerated storage conditions makes it particularly problematic in postharvest management.

Similarly, species within the genus *Colletotrichum*, particularly those in the *C. acutatum* species complex, cause anthracnose disease in strawberry [12]. These fungi exhibit a hemibiotrophic lifestyle, initially establishing a biotrophic relationship with host tissues before transitioning to a necrotrophic phase that leads to extensive tissue damage. *Colletotrichum* spp. can infect multiple plant organs, including leaves, stolons, crowns, and fruits, causing symptoms such as necrotic lesions, crown rot, and fruit decay. In severe cases, anthracnose can cause up to 50% yield loss and significant plant mortality, particularly under nursery and field conditions. [3]. The global diversity of *Colletotrichum* species associated with strawberry further complicates disease management, as multiple species complexes coexist and vary in pathogenicity and environmental adaptability.

The infection cycle of these phytopathogens involves several stages, including spore dissemination, adhesion, germination, penetration, colonization, and sporulation. Spores are typically dispersed by wind,

water, and agricultural activities, and once deposited on the plant surface, they germinate under favorable environmental conditions. The formation of specialized infection structures, such as appressoria, allows the pathogen to penetrate host tissues, often aided by the secretion of cell wall-degrading enzymes and phytotoxins. These biochemical processes facilitate tissue maceration, nutrient acquisition, and rapid colonization. [13].

Environmental conditions play a crucial role in disease epidemiology. High relative humidity (>90%), prolonged leaf wetness, and moderate temperatures significantly enhance fungal growth and infection rates. Additionally, dense planting systems, poor ventilation, and inadequate sanitation practices contribute to the spread and persistence of pathogens within the crop. Under such conditions, epidemics can develop rapidly, particularly during the flowering and fruiting stages, when plant tissues are more susceptible. [9, 13]

The management of fungal diseases in strawberry crops has traditionally relied on the application of synthetic fungicides. However, the intensive and repeated use of these chemicals has led to the development of fungicide-resistant strains, particularly in *Botrytis cinerea*, a high-risk pathogen for resistance development. This resistance reduces the effectiveness of chemical control strategies and poses a significant challenge for sustainable disease management. Furthermore, growing concerns about environmental contamination and food safety have intensified demand for alternative control methods.

Given these challenges, there is growing interest in developing sustainable strategies, including biological control and plant-derived compounds, to manage fungal diseases in strawberry production systems. A comprehensive understanding of the biology, infection mechanisms, and ecological behavior of phytopathogenic fungi is essential for designing effective and environmentally friendly management approaches.

#### 4. Conventional management and control of fungal disease in *Fragaria* spp.

Conventional management of fungal diseases in *Fragaria* spp. relies primarily on synthetic fungicides,

supplemented by cultural and agronomic practices to reduce pathogen pressure. Fungicides such as captan, boscalid, fenhexamid, and strobilurins are widely used to control key pathogens, including *Botrytis cinerea* and *Colletotrichum spp.*, particularly during the flowering and fruit development stages, when infection risk is highest [14, 15]. These chemical treatments are typically integrated with cultural strategies such as crop rotation, removal of infected plant residues, optimization of plant density, and improved ventilation to minimize humidity and limit pathogen proliferation [16]. In protected cultivation systems, environmental control and sanitation practices are also essential components of disease management. However, the intensive and repeated application of fungicides has led to the development of resistant fungal populations, particularly in *B. cinerea*, a high-risk pathogen due to its genetic variability and rapid adaptability [17]. Additionally, concerns regarding environmental contamination, effects on non-target organisms, and the accumulation of chemical residues in fruits have posed significant challenges to sustainable strawberry production [18]. These limitations highlight the need for integrated and alternative approaches that reduce dependency on chemical control while maintaining effective disease management.

##### 5. Plant Extracts as an Alternative for Phytosanitary Control

The growing limitations of conventional chemical control strategies have spurred the exploration of plant-derived extracts as sustainable alternatives for phytosanitary management. Plant extracts have gained significant attention due to their biodegradability, lower environmental impact, and reduced risk of generating resistant pathogen populations compared to synthetic fungicides. [19, 20]. These natural products contain a diverse array of bioactive secondary metabolites that play key roles in plant defense mechanisms and exhibit antimicrobial activity against a broad spectrum of phytopathogens. [21, 22].

Plant extracts can be obtained from various plant organs, including leaves, roots, stems, flowers, and seeds, through extraction methods such as maceration, infusion, hydrodistillation, and solvent extraction. The choice of extraction method and

solvent significantly influences the chemical composition and biological activity of the resulting extract. Polar solvents such as methanol and ethanol are particularly effective for extracting phenolic compounds, whereas non-polar solvents are more suitable for isolating essential oils rich in terpenoids. [23, 24].

The antifungal activity of plant extracts is primarily attributed to secondary metabolites such as phenolics, flavonoids, terpenoids, alkaloids, and saponins. These compounds exert their effects through multiple mechanisms, including disruption of fungal cell membrane integrity, inhibition of ergosterol biosynthesis, interference with enzymatic systems, and induction of oxidative stress within fungal cells. [25, 26]. Additionally, some plant extracts have been reported to act as elicitors of plant defense responses, enhancing resistance against pathogen infection.

In strawberry production, plant extracts have shown promising results against major fungal pathogens, including *Botrytis cinerea* and *Colletotrichum spp.* Studies have demonstrated that plant-derived compounds can reduce mycelial growth, inhibit spore germination, and decrease disease incidence in both preharvest and postharvest conditions. [18]. Moreover, certain extracts help maintain fruit quality by reducing the microbial load and delaying senescence, which is particularly relevant for highly perishable fruits such as strawberries.

Despite these advantages, the practical application of plant extracts in agricultural systems faces several challenges. These include variability in chemical composition due to environmental and genetic factors, limited stability of active compounds, and the need to standardize extraction and application protocols. Furthermore, large-scale production and formulation of plant-based biofungicides require optimization to ensure efficacy, safety, and economic feasibility.

Overall, plant extracts represent a promising component of integrated disease management strategies, offering a more sustainable approach to controlling phytopathogens in strawberry crops. Continued research is necessary to improve their consistency, understanding of their mode of action,

and field-level validation to support their adoption in commercial agriculture.

#### 6. Plant secondary metabolites with antifungal potential

Plant secondary metabolites are a diverse group of bioactive compounds that play a fundamental role in plant defense against biotic and abiotic stresses. These compounds are not directly involved in primary metabolic processes but contribute significantly to plant survival by protecting against phytopathogens, herbivores, and environmental stressors such as ultraviolet radiation. [27]. Among the most relevant classes of secondary metabolites with antifungal activity are alkaloids, tannins, essential oils (terpenoids), flavonoids, and saponins.

Alkaloids are nitrogen-containing compounds known for their potent antimicrobial properties. Their antifungal activity is primarily attributed to their ability to disrupt DNA replication, protein synthesis, and cellular metabolism in fungal pathogens. [23]. Tannins, a group of polyphenolic compounds, exert antimicrobial effects through protein precipitation and enzyme inhibition, thereby limiting microbial growth and pathogenicity. [28].

Essential oils, primarily composed of terpenoids, are volatile compounds with broad-spectrum antimicrobial activity. Their mechanism of action involves disruption of cell membrane integrity, leading to increased permeability and leakage of cellular contents. [25, 26]. However, their volatility and sensitivity to environmental factors such as temperature and ultraviolet radiation may limit their persistence under field conditions.

Flavonoids are phenolic compounds widely distributed in plants, playing important roles in signaling, defense, and plant–microbe interactions. They contribute to antifungal activity by inducing oxidative stress, inhibiting fungal enzymes, and affecting cell wall integrity. [28]. Additionally, flavonoids are involved in the establishment of beneficial symbiotic relationships, such as mycorrhizae, which can indirectly enhance plant resistance.

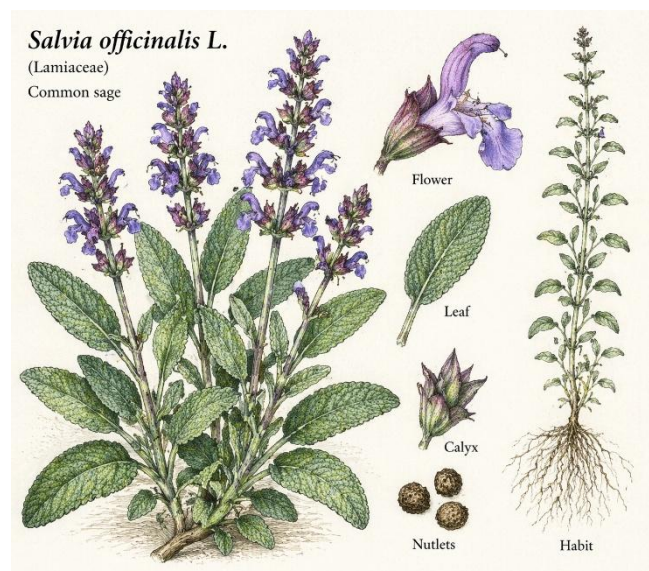
Saponins are glycosidic compounds with strong antifungal and insecticidal properties. Their activity primarily involves interaction with membrane sterols, leading to pore formation, increased membrane permeability, and eventual cell lysis. [29]. Overall, these classes of secondary metabolites are widely distributed across plant species and are largely responsible for the antimicrobial and antifungal properties observed in plant extracts. Mechanisms, including disruption of cell membrane integrity, inhibition of key metabolic pathways, and induction of oxidative stress in fungal cells, primarily mediate their bioactivity. [25, 26]. Additionally, compounds such as saponins and phenolics have been shown to interact with membrane sterols and proteins, thereby increasing permeability and causing cellular dysfunction. [26, 29]. The diversity and multifunctionality of these metabolites make them promising candidates for developing natural biofungicides in sustainable agricultural systems. Consequently, their study has become a central focus in plant protection research, particularly in the search for environmentally friendly alternatives to synthetic fungicides. [27, 30].

#### 7. *Salvia officinalis* L.

*Salvia* (Figure 1) belongs to the mint family (Lamiaceae), subfamily Nepetoideae, tribe Mentheae, and genus *Salvia*. This genus is the largest within the Lamiaceae family, comprising approximately 1,000 species distributed across Europe (particularly the Mediterranean region), Southeast Asia, and Central and South America. *Salvia officinalis* is a perennial subshrub with opposite, simple leaves, whitish pubescence on the underside, and a green to grayish-green upper surface. The stems are erect or procumbent, highly branched, and typically dark green, covered with fine hairs. [31].

This species grows in a wide range of environments, including grasslands, rocky areas, cliffs, walls, plains, and abandoned or arid slopes. It thrives under temperate to warm-temperate climates and does not tolerate waterlogged soils or excessive moisture. Although it is considered a thermophilic, xerophytic plant with high drought tolerance, prolonged dry periods may adversely affect its development and productivity. Phytochemical analyses of essential oils

from aerial parts have identified approximately 120 bioactive compounds, including fatty acids, carbohydrates, alkaloids, glycosidic saponins, terpenes, phenolic acids, flavonoids, and polyacetylenes [32].



**Figure 1.** Botanical illustration of *Salvia officinalis* L. (Lamiaceae), showing morphological characteristics such as inflorescences, leaves, and overall plant structure. The species is characterized by opposite, simple, pubescent, grayish-green leaves and purple-blue bilabiate flowers arranged in spikes. This representation highlights key taxonomic features for its identification and its use as a medicinal and bioactive plant.

### 7.1 Methods for Obtaining Plant Extracts

Currently, a wide range of techniques is available for extracting bioactive compounds from various plant organs, including leaves, flowers, stems, seeds, roots, and fruits. Among the most commonly used methods are steam distillation, hydrodistillation, decantation, filtration, and chromatography, which are widely used in the pharmaceutical, cosmetic, and food industries for the isolation, extraction, and purification of plant-derived compounds such as essential oils [33].

The extraction process involves transferring the active compounds from plant material into a solvent, typically water or alcohol. This process can be performed under cold or hot conditions, depending on the nature of the compounds to be extracted. The resulting product may be a liquid extract or a more concentrated, viscous substance, depending on the intended application. One of the most widely used extraction techniques is maceration. This method is performed at room temperature and involves soaking finely ground plant material in a solvent (such as water or ethanol) until the solvent penetrates the plant tissues and dissolves soluble components. [34]. The process typically takes between 2 and 14 days with occasional agitation. After extraction, the mixture is filtered, the plant residue is pressed to recover additional extract, and the solvent is removed—commonly using a rotary evaporator—to obtain the final concentrated extract

### 7.2. Extracts of *Salvia officinalis* L. for evaluating antifungal activity against phytopathogenic fungi

The increasing demand for sustainable alternatives to synthetic fungicides has intensified research on plant-derived extracts with antifungal potential. Among medicinal and aromatic plants, *Salvia officinalis* L. has received considerable attention due to its rich phytochemical composition and its documented antimicrobial properties. Extracts obtained from this species, particularly from leaves and aerial parts, contain a wide range of bioactive compounds, including terpenoids (e.g., thujone, camphor, and 1,8-cineole) and phenolic constituents (e.g., rosmarinic acid and flavonoids), which have been associated with antifungal activity against a broad spectrum of plant pathogens [35]. As summarized in Table 1, numerous studies have evaluated the antifungal efficacy of *S. officinalis* extracts from different plant parts using various extraction methods against target microorganisms. The most used extraction techniques include hydrodistillation for essential oil recovery and solvent extraction with ethanol, methanol, or water [35]. These methodological differences significantly influence the chemical composition and biological activity of the extracts, resulting in variability in antifungal performance. In general, essential oils tend to exhibit stronger inhibitory effects due to their high concentrations of

volatile compounds. In contrast, aqueous extracts may exhibit moderate activity while offering advantages in safety and environmental compatibility.

The studies compiled in Table 1 demonstrate that *S. officinalis* extracts are effective against several phytopathogenic fungi of agricultural importance, including *Fusarium*, *Botrytis*, *Colletotrichum*, *Penicillium*, and *Aspergillus* species. [36]. These pathogens cause significant economic losses in crops such as strawberries, where diseases like gray mold and anthracnose severely affect yield and postharvest quality. In vitro assays have consistently shown that sage extracts can inhibit mycelial growth, reduce spore germination, and alter fungal morphology, highlighting their potential as biofungicidal agents. The antifungal mechanisms of *S. officinalis* extracts are primarily related to the disruption of fungal cell membrane integrity, interference with ergosterol biosynthesis, and induction of oxidative stress within fungal cells. In addition, some studies have reported synergistic effects when sage extracts are combined with other plant-derived compounds, enhancing their inhibitory activity and expanding their spectrum of action. These findings suggest that *S. officinalis* could be integrated into multi-component formulations for improved phytosanitary control.

Despite these promising results, most studies remain limited to laboratory-scale evaluations, and there is still a lack of standardized protocols for extraction, dosage, and application. Furthermore, the variability in chemical composition arising from environmental factors, plant genotype, and extraction conditions poses a challenge to reproducibility and large-scale implementation. Therefore, further research is required to validate the efficacy of *S. officinalis* extracts under greenhouse and field conditions and to optimize their formulation and application strategies.

Overall, the evidence presented in Table 1 supports the potential of *Salvia officinalis* extracts as natural antifungal agents in crop protection systems. Their incorporation into integrated disease management strategies could help reduce reliance on synthetic fungicides and promote more sustainable agricultural practices.

In postharvest systems, *Salvia officinalis* extracts represent a promising strategy for controlling fungal decay and extending the shelf life of strawberry fruits, which are highly perishable due to their soft tissue, high water content, and intense metabolic activity. Postharvest losses are primarily associated with pathogens such as *Botrytis cinerea*, the causal agent of gray mold, which is considered the most important disease affecting strawberries during storage and distribution. [37]. Recent studies have demonstrated that plant-derived compounds, particularly essential oils, can effectively inhibit fungal growth by disrupting cell membrane integrity, causing leakage of cellular contents, and altering fungal morphology. In vivo applications, including fumigation, coatings, and nanoemulsion systems, have shown significant reductions in decay incidence and microbial load while preserving fruit quality attributes such as firmness, antioxidant content, and soluble solids. Moreover, advances in nanoencapsulation technologies have improved the stability and controlled release of essential oils, thereby enhancing their antifungal efficacy and making them comparable to conventional fungicides under postharvest conditions. Despite these advances, challenges remain regarding volatility, sensory impact, and compositional variability, which can affect consistency and consumer acceptance. Therefore, future research should focus on optimizing delivery systems, standardizing formulations, and validating plant-based antifungal treatments under commercial storage conditions to enable their practical implementation in postharvest disease management systems.

## 8. Future Perspectives and Challenges

Despite the promising antifungal potential of *Salvia officinalis* extracts, several challenges must be addressed before their widespread application in crop protection systems can be achieved. One of the main limitations is the variability in chemical composition associated with environmental conditions, plant genotype, harvest time, and extraction method, which directly affects reproducibility and efficacy. In addition, the lack of standardized protocols for extraction, formulation, and application complicates the comparison of results across studies and hinders the development of consistent biofungicidal products.

Table 1. Antifungal activity of *Salvia officinalis* L. extracts against phytopathogenic fungi under different extraction methods and experimental conditions.

Part of the plant that was used	Solvent used to extract compounds	Against what was evaluated	Results	Reference
Aerial parts of the plant	70% Ethanol	<i>Aspergillus fumigatus</i> , <i>Aspergillus versicolor</i> , <i>Aspergillus ochraceus</i> , <i>Aspergillus niger</i> , <i>Trichoderma viride</i> , <i>Penicillium funiculosum</i> , <i>Penicillium ochrochlorum</i> and <i>Penicillium verrucosum</i> .	The fungal strains analyzed were sensitive to all <i>Salvia</i> extracts.	[36]
Aerial parts of the plant	Hydrodistillation	<i>Fusarium graminearum</i>	The antifungal potential of thyme essential oil was demonstrated by the total inhibition of <i>Fusarium</i> mycelium growth across all concentrations.	[38]
Aerial parts of the plant	Hydrodistillation	<i>Fusarium oxysporum f.sp. albedinis</i>	Partial inhibition is observed in sage essential oil for all concentrations.	[39]
Aerial parts and roots of the plant	Ethanol	<i>Microsporium gypseum</i> , <i>Trichophyton mentagrophytes var erinacei</i> , and <i>Candida parapsilosis</i>	The essential oils of the four <i>Salvia</i> species analyzed indicated very high antifungal activity.	[40]
Dried plant	Hydrodistillation	<i>Fusarium graminearum</i>	The antifungal effect is temporary for <i>Fusarium graminearum</i>	[41]
Dried plant	Hydrodistillation	<i>Fusarium oxysporum f. sp.</i>	The essential oil of <i>S. officinalis</i> had the greatest impact on the development of the mycelium of <i>F. oxysporum f. sp.</i>	[42]
Leaves	Decoction and filtering	<i>Candida albicans</i> and <i>Saccharomyces cerevisiae</i>	The results showed that the aqueous extract of the test plant is effective at a concentration of 0.25 mg/ml against <i>C. albicans</i> and <i>S. cerevisiae</i> .	[43]
Aerial parts	Anhydrous sodium sulfate	<i>Botrytis cinerea</i> , <i>Penicillium expansum</i> , and <i>Rhizopus stolonifer</i>	Inhibition increased with increasing concentrations of <i>Salvia officinalis</i> oil for all tested strains.	[37]
Leaves	Hydrodistillation	<i>Aspergillus carbonarius</i>	0.3% of the essential oils of <i>L. nobilis</i> and <i>L. dentata</i> stopped the growth of <i>A. carbonarius</i> in the contact assay.	[44]

Another critical challenge is the limited number of studies conducted under greenhouse and field conditions, as most available data are derived from in vitro assays. This gap limits understanding of the actual performance of these extracts in complex agricultural environments.

Future research should focus on optimizing extraction techniques to maximize the yield of active compounds, as well as developing stable formulations—such as nanoencapsulation or emulsions—that enhance the persistence and bioavailability of bioactive constituents. Furthermore, it is essential to evaluate the synergistic effects of *S. officinalis* extracts with other plant-derived compounds or biological control agents to improve their antifungal spectrum and reduce required application doses. Toxicological assessments and studies on potential phytotoxic effects are also necessary to ensure safe application. Finally, integrating these natural products into existing integrated pest management (IPM) programs represents a key step toward reducing dependence on synthetic fungicides and promoting sustainable agricultural practices.

## 9. Conclusion

The evidence reviewed in this study highlights the significant potential of *Salvia officinalis* L. as a natural source of antifungal compounds for controlling phytopathogenic fungi. Its extracts, particularly essential oils and solvent-based preparations, have demonstrated inhibitory effects against a wide range of fungal pathogens of agricultural importance, including species of *Botrytis*, *Colletotrichum*, *Fusarium*, and *Penicillium*. These antifungal properties are primarily attributed to bioactive secondary metabolites, including terpenoids and phenolic compounds, which act through multiple mechanisms, including disruption of cell membranes, inhibition of ergosterol biosynthesis, and induction of oxidative stress.

However, despite the strong in vitro evidence, the transition from laboratory findings to practical agricultural applications remains limited. Addressing current challenges related to standardization, formulation, and field validation will be essential to exploit the potential of *S. officinalis* as a biofungicide

fully. In this context, incorporating sage-derived products into sustainable crop protection strategies offers a promising approach to reducing the environmental and health impacts associated with conventional fungicides while maintaining effective disease control in crops such as strawberries.

### Acknowledgments

This work was supported by UNAM Posdoctoral Program (POSDOC)

### Conflict of Interest

There are no conflicts of interest.

### References

- Van De Velde, F., et al., *Bioactive compounds and antioxidant capacity of Camarosa and Selva strawberries (Fragaria x ananassa Duch.)*. Foods, 2013. **2**(2): p. 120-131.
- Atazhanova, G.A., et al., *A review of botany, phytochemistry, and biological activities of Fragaria vesca and Fragaria viridis widespread in Kazakhstan*. Plants, 2025. **14**(13): p. 2027.
- Aljawasim, B.D., J.B. Samtani, and M. Rahman, *New insights in the detection and management of anthracnose diseases in strawberries*. Plants, 2023. **12**(21): p. 3704.
- Zhang, L., et al., *Characterization and fungicide sensitivity of Colletotrichum species causing strawberry anthracnose in eastern China*. Plant disease, 2020. **104**(7): p. 1960-1968.
- Zuccarelli, P., *Fungicidas: impacto en la salud y el medio ambiente*. TSI Group-Tecnosoluciones Integrales. URL: <https://tecnosolucionescr.net/blog/145-fungicidas-impacto-en-la-salud-y-el-medio-ambiente>, 2019.
- Fenta, L. and H. Mekonnen, *Microbial biofungicides as a substitute for chemical fungicides in the control of phytopathogens: Current perspectives and research directions*. Scientifica, 2024. **2024**(1): p. 5322696.
- Tijjani, H., C. Egbuna, and L.D. Carrol, *Biosynthesis of phytochemicals*, in *Phytochemistry*. 2018, Apple Academic Press. p. 37-78.
- Copetta, A. and B. Ruffoni, *Biodiversity and Breeding in Salvia officinalis L*, in *Breeding of Ornamental Crops: Annuals and Cut Flowers*. 2025, Springer. p. 263-296.
- Tane, M.-C., *The main fungal diseases in strawberries crop-review*. 2022.
- Tomas-Grau, R.H., et al., *Biological control of strawberry grey mold disease caused by Botrytis cinerea mediated by Colletotrichum acutatum extracts*. BioControl, 2020. **65**(4): p. 461-473.
- Manjunatha, L., et al., *Botrytis*, in *Compendium of Phytopathogenic Microbes in Agro-Ecology: Vol. I Fungi*. 2025, Springer. p. 75-96.
- Wang, N.-Y., B.B. Forcelini, and N.A. Peres, *Anthracnose fruit and root necrosis of strawberry are caused by a dominant species within the Colletotrichum acutatum species complex in the United States*. Phytopathology, 2019. **109**(7): p. 1293-1301.
- Singh, P.K., et al., *GROWTH AND SURVIVAL OF PLANT PATHOGENS*. India-482003 India-482003 This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage, 2023: p. 72.
- Petrasch, S., *Genetics of strawberry postharvest fruit quality and resistance to necrotrophic fungi*. 2020: University of California, Davis.
- Fernández-Ortuño, D., et al., *Independent emergence of resistance to seven chemical classes of fungicides in Botrytis cinerea*. Phytopathology, 2015. **105**(4): p. 424-432.
- Williamson, B., et al., *Botrytis cinerea: the cause of grey mould disease*. Molecular plant pathology, 2007. **8**(5): p. 561-580.
- Weber, R.W. and A. Petridis, *Fungicide resistance in Botrytis spp. and regional strategies for its management in Northern European strawberry production*. BioTech, 2023. **12**(4): p. 64.
- Romanazzi, G., et al., *Integrated management of postharvest gray mold on fruit crops*. Postharvest Biology and Technology, 2016. **113**: p. 69-76.
- Isman, M.B., *Botanical insecticides in the twenty-first century—fulfilling their promise?* Annual Review of Entomology, 2020. **65**(1): p. 233-249.
- Deresá, E.M. and T.F. Diriba, *Phytochemicals as alternative fungicides for controlling plant diseases: A comprehensive review of their efficacy, commercial representatives, advantages, challenges for adoption, and possible solutions*. Heliyon, 2023. **9**(3).
- Aremu, A.O., et al., *Plants as an alternative to the use of chemicals for crop protection against biotic threats: trends and future perspectives*. European Journal of Plant Pathology, 2024. **170**(4): p. 711-766.
- Souto, A.L., et al., *Plant-derived pesticides as an alternative to pest management and sustainable agricultural production: Prospects, applications and challenges*. Molecules, 2021. **26**(16): p. 4835.
- Cowan, M.M., *Plant products as antimicrobial agents*. Clinical microbiology reviews, 1999. **12**(4): p. 564-582.
- Borges, A., et al., *Antibacterial activity and mode of action of selected glucosinolate hydrolysis products against bacterial pathogens*. Journal of food science and technology, 2015. **52**(8): p. 4737-4748.
- Bakkali, F., et al., *Biological effects of essential oils—a review*. Food and chemical toxicology, 2008. **46**(2): p. 446-475.
- Hyldegaard, M., T. Mygind, and R.L. Meyer, *Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components*. Frontiers in microbiology, 2012. **3**: p. 12.
- Wink, M., *Annual plant reviews, functions and biotechnology of plant secondary metabolites*. 2010: John Wiley & Sons.
- Daglia, M., *Polyphenols as antimicrobial agents*. Current opinion in biotechnology, 2012. **23**(2): p. 174-181.
- Osbourne, A., *Saponins and plant defence—a soap story*. Trends in plant science, 1996. **1**(1): p. 4-9.
- Sharifi-Rad, J., et al., *Biological activities of essential oils: From plant chemocology to traditional healing systems*. Molecules, 2017. **22**(1): p. 70.
- Alamgir, A., *Pharmacognostical Botany: Classification of medicinal and aromatic plants (MAPs), botanical taxonomy, morphology, and anatomy of drug plants, in Therapeutic use of medicinal plants and their extracts: Volume 1: Pharmacognosy*. 2017, Springer. p. 177-293.
- Garg, D., *A review of therapeutic properties and uses of Salvia officinalis*. Journal of Pharma Insights and Research, 2024.
- Othman, M., et al., *Optimal methods for evaluating antimicrobial activities from plant extracts*. Journal of Microbiological Methods, 2011. **84**(2): p. 161-166.
- Veličković, D.T., et al., *Extraction of flavonoids from garden (Salvia officinalis L.) and glutinous (Salvia glutinosa L.) sage by ultrasonic and classical maceration*. Journal of the Serbian Chemical Society, 2007. **72**(1): p. 73-80.
- Ghorbani, A. and M. Esmailizadeh, *Pharmacological properties of Salvia officinalis and its components*. Journal of traditional and complementary medicine, 2017. **7**(4): p. 433-440.
- Mocan, A., et al., *Chemical constituents and biologic activities of sage species: A comparison between Salvia officinalis L., S. glutinosa L. and S. transsylvanica (schur ex griseb. & schenk) schur*. Antioxidants, 2020. **9**(6): p. 480.
- El Ouadi, Y., et al., *Essential oil composition and antifungal activity of Salvia officinalis originating from North-East Morocco, against postharvest phytopathogenic fungi in apples*. Der Pharma Chemica, 2015. **7**(9): p. 95-102.

38. Cocan, I., et al., *Phytochemical screening and biological activity of Lamiaceae family plant extracts*. Experimental and Therapeutic Medicine, 2018. **15**(2): p. 1863-1870.
39. Barkaoui, H., et al., *Antifungal activity of the essential oils of Rosmarinus officinalis, Salvia officinalis, Lavandula dentata and Cymbopogon citratus against the mycelial growth of Fusarium oxysporum f. sp. Albedinis*. Arabian Journal of Medicinal and Aromatic Plants, 2022. **8**(1): p. 108-133.
40. Tan, N., et al., *Antimycobacterial and antifungal activities of selected four Salvia species*. Records of Natural Products, 2016. **10**(5): p. 593.
41. Tomescu, A., et al., *Chemical composition and protective antifungal activity of Mentha piperita L. and Salvia officinalis L. essential oils against Fusarium graminearum spp.* Revista de Chimie, 2015. **66**(7): p. 1027-1030.
42. Yilar, M. and I. Kadioglu, *Antifungal activities of some Salvia species extracts on Fusarium oxysporum f. sp. radialis-lycopersici (Forl) mycelium growth in-vitro*. Egyptian Journal of Biological Pest Control, 2016. **26**(1): p. 115-118.
43. Maliki, I., et al., *Phytochemical screening and the antioxidant, antibacterial and antifungal activities of aqueous extracts from the leaves of Salvia officinalis planted in Morocco*. Moroccan Journal of Chemistry, 2021. **9**(2): p. J. Chem. 9 N° 2 (2021) 354-368.
44. Dammak, I., et al., *Evaluation of antifungal and anti-ochratoxigenic activities of Salvia officinalis, Lavandula dentata and Laurus nobilis essential oils and a major monoterpene constituent 1, 8-cineole against Aspergillus carbonarius*. Industrial Crops and Products, 2019. **128**: p. 85-93.