

EVALUATION OF THE ANTIMICROBIAL POTENTIAL OF SATUREJA MONTANA L. ESSENTIAL OIL – A BRIEF NARRATIVE REVIEW

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ABSTRACT

Antimicrobial resistance is one of the greatest challenges facing contemporary medicine, requiring a reassessment of natural bioactive agents as adjuvants in both therapy and industry. This paper systematically analyses the therapeutic potential of essential oil extracted from *Satureja montana* L., a Mediterranean species known for its phytochemical profile dominated by phenolic monoterpenes such as carvacrol and thymol. The literature review highlights a direct correlation between chemotype variability, conditioned by ecopedological factors and altitude, and the intensity of the biocidal response. Experimental data confirm considerable efficacy against a wide spectrum of pathogens, particularly Gram-positive, Gram-negative bacteria and fungi. The implications of essential oils are wide-ranging, extending across fields such as public health, food industry, animal husbandry and agriculture. Particular interest is given to the synergy between oil and antibiotics such as gentamicin, as well as two mixtures of different essential oils, and to their ability to inhibit the formation of bacterial biofilms. The conclusion of the synthesis indicates that *S. montana* is a versatile resource for new antimicrobial strategies. Although certain resistance mechanisms require further research, the species remains a promising candidate for its therapeutic potential, raising the essential question of how these results can be effectively transferred to *in vivo* treatments.

KEY WORDS: antimicrobial activity; phenolic monoterpenes; winter savory; biocidal properties; compound synergy

INTRODUCTION

In the current global public health landscape, antibiotic resistance has become one of the most serious threats to health security, threatening to invalidate the major advances of modern medicine and thus becoming a strategic priority for research. The scale of this phenomenon is confirmed by high-impact epidemiological studies, which

draw attention to the need to identify new bioactive agents capable of circumventing the resistance mechanisms developed by pathogens (GBD 2021 Antimicrobial Resistance Collaborators, 2024).

Among the phytotherapeutic resources with potential relevance is the species *Satureja montana* L. (syn. *Clinopodium montanum* (L.) Kuntze), commonly known as winter savory or wild savory, illustrated in Figure 1. This aromatic perennial plant occupies an ecological and cultural niche in the Mediterranean basin and the Balkan regions, with a wide geographical distribution in countries such as Albania, Croatia, Serbia, and Italy. The species has a long history of use in both traditional medicine and gastronomy, being empirically recognized for its antiseptic, carminative, and digestive properties (Serrano *et al.*, 2011). In recent decades, popular observations have been validated due to increased interest from the scientific community, which has generated evidence regarding the complex phytochemical profile and broad spectrum of biological activities of this species (Hajdari *et al.*, 2016; Vilmosh *et al.*, 2022).



FIG. 1. *Satureja montana* L. from Jacob Sturm, public domain, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Satureja_montana_-_Deutschlands_flora_in_abbildungen_nach_der_natur_-_vol._20_-_t._17.jpg, accessed on 23 February 2026)

A fundamental feature of the species *S. montana* is its high phytochemical variability. This is due to the dynamic interaction between genetic background and ecopedological factors. This chemical "plasticity" is significantly influenced by geographical origin, altitude of the harvesting area, soil composition, and the ontogenetic stage of the plant at the time of processing (Kuštrak *et al.*, 1996; Mirjana & Nada, 2004). Advanced analyses have identified three main chemotypes: carvacrol-dominant, thymol-dominant, and mixed. The compounds carvacrol and thymol are shown in Figure 2. While the carvacrol-rich chemotype has increased antimicrobial potency, the thymol-dominant chemotype has additional antioxidant and wound-healing benefits (Čutović *et al.*, 2025). At the same time, studies show that with increasing altitude, the chemotype differentiates, containing increased amounts of linalool, terpinen-4-ol, and cis-sabinene hydrate, but decreased amounts of thymol and carvacrol (Mihajilov-Krstešević *et al.*, 2014).



FIG. 2. Visualization in Chimera (Pettersen *et al.*, 2004) of the isomers Carvacrol (left) and Thymol (right)

Recent data (Coban *et al.*, 2025) describe a typical profile often composed of carvacrol ($\approx 49\%$), thymol ($\approx 34\%$), and p-cymene, closely reflecting previous phytochemical reports. These secondary metabolites are not just chemical markers but play an active role in modulating overall biological efficacy, influencing how extracts interact with microbial cells (Said-Al Ahl *et al.*, 2024; Mirjana & Nada, 2004).

The antimicrobial efficacy of *S. montana* essential oil (EO) is mainly derived from the intrinsic properties of phenolic monoterpenes. The mechanism of action is complex: carvacrol and thymol act synergistically to destabilize and disrupt the integrity of the cytoplasmic membrane of pathogens (Said-Al Ahl *et al.*, 2024; Coban *et al.*, 2025). Experimental data highlight the high sensitivity of Gram-positive bacteria and yeasts in contact with this oil (Serrano *et al.*, 2011; Marin *et al.*, 2012).

However, the resistance of certain species remains a significant barrier to its universal clinical use. A notable example is *Pseudomonas aeruginosa*, which exhibits

high intrinsic resistance to the action of the oil's lipophilic components; this tolerance is attributed to its complex structure, in particular the presence of a polysaccharide capsule that acts as a protective filter, limiting the penetration of bioactive compounds (Maravić-Vlahoviček *et al.*, 2025).

Beyond its direct bactericidal action, an aspect of clinical interest is the ability of EO to inhibit the formation of biofilms, bacterial structures that are resistant to conventional treatments (Rinaldi *et al.*, 2021). Furthermore, its therapeutic potential is amplified by the strong synergistic effects observed in combination with conventional antibiotics. For example, the synergy between *S. montana* EO and gentamicin potentiated the activity of the antibiotic, offering a potential solution for combating multidrug-resistant strains through adjuvant therapies (Vitanza *et al.*, 2019; Abbad *et al.*, 2025).

The aim of this paper is to provide an up-to-date summary of the literature and information on the antimicrobial effect of *S. montana* essential oil. The goal is to verify whether this EO can indeed be a real solution for current treatments, attempting to answer a key question: "To what extent does *Satureja montana* essential oil exhibit biocidal efficacy against a diverse spectrum of pathogens (bacterial, fungal, and parasitic) in the context of current antimicrobial resistance, and what are the mechanisms of action?".

LITERATURE REVIEW

This literature review was conducted by documenting and collecting information from scientific databases such as Web of Science and Google Scholar. The search strategy was based on the use of keywords such as "*Satureja montana*" "essential oil" and "antimicrobial activity", which concluded with the selection of 36 articles. Articles investigating the antimicrobial potential of *S. montana* essential oil on a wide range of microorganisms, particularly Gram-positive and Gram-negative bacteria and pathogenic fungi, were included in the review. Both *in vitro* and *in vivo* data were selected. The extracted data were processed to highlight general trends in the field, discrepancies between the results of different research groups, and the determining factors influencing the variability of antimicrobial activity, thus providing a solid basis for further discussions on the mechanisms of action and therapeutic potential of this essential oil.

The studies analyzed highlighted a link between the biological activity of *Satureja montana* EO and its chemical composition, due in particular to the presence of carvacrol, p-cymene, and γ -terpinene. These compounds are involved in destabilizing

microbial cell membranes, which could explain the oil's antimicrobial activity. Based on the scope of application, the results identified in the literature were organized into three main categories: 1. Implications in the field of animal husbandry and veterinary medicine; 2. Plant pathology and crop protection; and 3. Impact on public health and food safety.

1. The benefits of essential oils in veterinary medicine and animal husbandry

In the veterinary field, a study investigated the activity of *S. montana* EO against bacteria responsible for bovine mastitis, including *Streptococcus* spp. β -hemolytic, as well as against other pathogens such as *Staphylococcus* spp., *Escherichia coli*, *Klebsiella oxytoca*, and *Cronobacter sakazakii* (Kovačević *et al.*, 2021). The antibacterial effect is supported by the antioxidant properties of the oil, which contribute to the neutralization of free radicals and the inhibition of lipid peroxidation, protecting host cells from oxidative stress generated during the infectious process (Kovačević *et al.*, 2021).

In another *in vitro* study, the intestinal parasite *Anisakis simplex*, present in fish populations, was negatively affected by the EO of *S. montana* (*montana* and *variegata* subspecies) (Les *et al.*, 2024). These EOs exhibit significant nematocidal activity for both subspecies, causing complete inactivation of *A. simplex* larvae within 24 hours. This action is facilitated by the inhibition of the enzyme acetylcholinesterase and severe disruption of the parasite's nervous system, which prevents its ability to penetrate tissues and, implicitly, cause infection (Les *et al.*, 2024).

S. montana EO also showed pronounced efficacy in liquid microdilution tests performed on thirty isolated strains of avian *E. coli*. The biofilm inhibition capacity was also superior when the EO was administered via nanoemulsion. However, it is important to note that none of the variants tested led to the complete eradication of already formed biofilms (Rinaldi *et al.*, 2021).

Other tests have indicated that the administration of EO at certain concentrations reduces the development of avian pathogens such as *S. aureus* and *E. coli* (Santos *et al.*, 2019). This potency was also confirmed by the disc diffusion method, where the inhibition zones showed a visible effect depending on the dose administered. Beyond its disinfectant role, integrating EO into the diet of birds can stimulate their growth, providing a sustainable alternative to antibiotics and capitalizing on agro-industrial waste according to the principles of the circular economy (Santos *et al.*, 2019).

The synergistic effect between *S. montana* EO and the equimolar mixture of *Origanum vulgare* and *Thymus vulgaris* EOs demonstrates, in a similar study, increased efficacy in combating strains of *E. coli* involved in environmental contamination, isolated from avian feces. The results show that even in the case of strains resistant to

ampicillin and amoxicillin-clavulanic acid, their association with *S. montana* EO reduces microbial activity and decreases the minimum inhibitory concentration (Cagnoli *et al.*, 2024).

2. Applications in plant pathology and crop protection

S. montana EO has also proven its effectiveness in plant protection. For example, nanotechnological systems based on montmorillonite clay to combat *Xanthomonas euvesicatoria*, the pathogen responsible for bacterial spot in *Solanum lycopersicum*. In these systems, montmorillonite encapsulates the oil, forming nanosystems that protect the active compounds and allow their controlled release, inducing a metabolic response against the pathogen and reducing the symptoms of blight (Oliveira-Pinto *et al.*, 2025). Another study uses zein as a nanotechnological particle system, with similar results. EO, released gradually, is suitable for treating the disease in tomatoes, reducing infection with *Xanthomonas spp.* (Oliveira-Pinto *et al.*, 2021).

In kiwi crops (*Actinidia spp.*), the phytopathogen *Pseudomonas syringae* pv. *actinidiae* is responsible for the development of kiwi fruit bacterial canker. EO from *S. montana* may represent an alternative to current bactericides or copper-based compounds used in the agricultural industry, due to its increased concentration of carvacrol, unlike other essential oils, such as *Mentha pulegium*, which is rich in pulegone. Through cellular mechanisms, the oil offers a dual control strategy against the pathogen *P. syringae* pv. *actinidiae*, both by destroying it and by stimulating physiological reactions that protect the plant against the pathogen (Oliveira-Fernandes *et al.*, 2023).

When used against *Acrobasis advenella* in *Aronia melanocarpa* crops, *S. montana* EO highlighted a dual physiological impact. Its application had a positive effect on the mineral profile and chlorogenic acid content of the fruit, but it also had a high phytotoxic effect, resulting in a reduction in the weight of the aronia fruit and affecting the vigor of the shrubs, which limits its practical applicability even at low concentrations (Górska-Drabik *et al.*, 2024).

Another study investigated the antifungal activity of EOs from five Mediterranean aromatic species (*Lavandula × intermedia*, *Salvia lavandulifolia*, *Satureja montana*, *Thymus mastichina*, *T. vulgaris*). EO from *S. montana* showed increased antifungal activity against the pathogenic fungus *Cladobotryum mycophilum*, responsible for Cobweb disease in *Agaricus bisporus* crops (Gea *et al.*, 2019).

3. Impact on public health and food safety

In terms of public health, *S. montana* EO is particularly relevant due to its antimicrobial effect. For example, four species of the genus *Satureja* sp. (*S. alpina*, *S.*

calamintha, *S. montana*, *S. hortensis*) were analyzed as adjuvants in classical antibiotic therapy to observe the synergistic activity between EOs and antibiotics (Abbad et al., 2025). Combinations with gentamicin reduced inhibitory concentrations for infections with bacteria such as *Pseudomonas aeruginosa*, *S. aureus*, *E. coli*, *Micrococcus luteus*, *Bacillus subtilis*, and *Klebsiella pneumoniae*. In the case of fungal infections, *S. montana* oil showed different effects together with amphotericin B against some *Candida* spp. (*C. albicans*, *C. glabrata*, *C. krusei*, *C. parapsilosis*), depending on the strain tested. The strongest synergistic result occurs when the EO is combined with gentamicin in Gram-negative bacteria such as *E. coli*, and *P. aeruginosa* (Abbad et al., 2025).

The impact of *S. montana* EO depends on the extraction method; oil obtained from dried plants showed the strongest bactericidal effect. Promising results were obtained against *B. subtilis*, *S. aureus*, and *E. coli*, while *P. aeruginosa* showed more pronounced resistance, results consistent with other articles (Djordjevic et al., 2021).

The antimicrobial activity against Gram-positive and Gram-negative bacteria was analyzed in a recent study, demonstrating the high potency of *S. montana* EO *in vitro*. The results obtained by the disc diffusion method showed extensive inhibition zones, with relevant results against *S. aureus* and *Enterococcus faecalis*, while *P. aeruginosa* showed the highest resistance to the extract (Pašić et al., 2025).

Another study looking at infections with the pathogen *P. aeruginosa* found that the dosage of *S. montana* EO has increased relevance, with paradoxical effects. At low concentrations, planktonic growth was stimulated, while at high concentrations, it was significantly inhibited but stimulated biofilm formation and pyocyanin production (Maravić-Vlahoviček et al., 2025).

Analysis of the *S. montana* subsp. *montana* and *variegata* EOs showed that they have strong antimicrobial activity, especially against Gram-positive bacteria, with a biocidal effect against *S. aureus*, *Enterococcus faecalis*, *C. albicans*, and *Bacillus cereus*. EOs proved to be effective even at certain low minimum inhibitory concentrations, with well-defined disc inhibition zones (Aćimović et al., 2022).

In the case of *Mycobacterium abscessus* strains, one study shows that *S. montana* EO may be an alternative to conventional antibiotics applied *in vitro*, destroying all stages of pathogen development (Cao et al., 2024). At the same time, the article draws attention to the cytotoxic effect of EO when applied *in vivo*, except for topical application (Cao et al., 2024).

Aflatoxins secreted by *Aspergillus flavus* pose a risk to public health through food and water contamination. EOs from *S. montana* and *Origanum virens* were used to observe the effects on *A. flavus* strains. Although both essential oils reduced the

reproductive capacity of *A. flavus*, only *S. montana* significantly decreased aflatoxin production (García-Díaz *et al.*, 2020).

Similar results were obtained in studies in 2021 and 2022, where *S. montana*, *Cymbopogon flexuosus*, and *Myristica fragrans* EOs were tested against cultures of *A. flavus* and *Aspergillus ochraceus*. Both pathogen species were inhibited by the administration of EOs at specific concentrations, while also reducing the secretion of the toxic compounds aflatoxin B1 and B2 and ochratoxin A by blocking ergosterol synthesis (Rezende *et al.*, 2021; Rezende *et al.*, 2022).

In health problems such as chronic periodontitis, *Porphyromonas gingivalis* is the pathogen responsible for this condition. *S. montana* EO showed higher efficacy in treating the condition compared to *Leptospermum scoparium* EO, significantly reducing the hydrophobicity of the pathogen and biofilm formation (Yuan *et al.*, 2025).

Regarding the food industry, the effects of *S. montana* EO and *S. montana* together with *S. hortensis* and *Origanum majorana* on turkey sausage production were analyzed. *Satureja montana* EO has a strong antibacterial action against the pathogens *Listeria monocytogenes*, *E. coli*, and *Salmonella enteritidis*. In addition, the oil inhibits the growth of bacteria involved in food spoilage and limits the accumulation of compounds such as tyramine and cadaverine, making it a possible adjuvant in extending the shelf life of food (Šojić *et al.*, 2023).

Another study looking at implications in the food industry highlights that the antimicrobial efficacy of *S. montana* EO is increased by synergistic mixtures, particularly with *Ocimum basilicum*. These combinations extend the spectrum of action to Gram-positive bacteria such as *S. aureus*, *B. cereus*, *L. monocytogenes*, and *E. faecalis*, as well as Gram-negative bacteria such as *E. coli*, *Salmonella typhimurium*, *P. aeruginosa*, and *K. pneumoniae*, with Gram-negative bacteria showing a more pronounced sensitivity to synergistic effects. In addition, nanoencapsulation of these mixtures in chitosan matrices optimizes the stability of bioactive compounds, allows controlled release of carvacrol and linalool, and reduces the intensity of the characteristic aroma of *S. montana* EO, facilitating its use as a biopreservative in food products (Đorđević *et al.*, 2025).

The synergy between *S. montana* EO and *Origanum heracleoticum* has proven to be relevant in food protection. Notable results are observed in the case of *S. typhimurium*, *E. coli*, *S. aureus*, *B. cereus*, and *L. monocytogenes*. These results support *S. montana* EO, especially in synergistic formulations, as a viable natural preservative for extending the shelf life and safety of fresh food products (Kocić-Tanackov *et al.*, 2026). A recent study uses the integration of *S. montana* EO into biodegradable polymer

matrices obtained from plum residues resulting from cold pressing of pits, with food implications. The matrices obtained after this process demonstrate improved resistance to moisture and increased antimicrobial and antifungal activity against microorganisms such as *A. ochraceus* and *S. aureus*. In addition, these matrices transform plant byproducts into a sustainable solution for preserving food quality (Pantić *et al.*, 2025).

DISCUSSIONS

Analysis of the literature indicates that the antimicrobial efficacy of *Satureja montana* is strictly conditioned by the interaction between genotype, environmental factors, and extraction technology. Phytochemical variability, correlated with altitude and ontogenetic stage, explains the fluctuations in minimum inhibitory values reported in studies (Mihajilov-Krstev *et al.*, 2014; Kuštrak *et al.*, 1996). This compositional heterogeneity requires rigorous selection of plant material depending on the intended purpose: the chemotype rich in carvacrol is targeted for its biocidal activity, while variants rich in thymol may offer advantages in tissue regeneration and antioxidant protection processes (Čutović *et al.*, 2025).

In the context of multidrug-resistant strains or latent phases of bacteria such as *Mycobacterium abscessus*, phenolic compounds manage to destabilize the cell structure (Cao *et al.*, 2024). However, the resistance of pathogens such as *Pseudomonas aeruginosa*, mediated by complex structural barriers, highlights the limitations of this resource and the need for extremely precise dosing to avoid the paradoxical effects of stimulating virulence (Maravić-Vlahoviček *et al.*, 2025).

A notable advance in research is the use of nanotechnology to optimize the delivery of these compounds, such as the formulation of nanoemulsions or encapsulation in polymeric matrices (chitosan, montmorillonite), which has demonstrated an improved ability to penetrate biofilms formed by *S. aureus* or *E. coli* and be effective against *X. euvesicatoria* (Đorđević *et al.*, 2025; Oliveira-Pinto *et al.*, 2025). Furthermore, the synergy observed between *S. montana* and antibiotics such as gentamicin is perhaps the most valuable direction of research, offering the possibility of reducing synthetic antibiotic doses and, implicitly, the selective pressure for resistance (Abbad *et al.*, 2025; Vitanza *et al.*, 2019).

The synthesis of current data confirms that *S. montana* EO is a promising adjuvant in modern antimicrobial strategies, with applications ranging from veterinary medicine to food safety. Its primary advantage is not as a substitute for antibiotics, but for its synergistic action and ability to inhibit biofilms resistant to standard treatments (Abbad *et al.*, 2025; Vitanza *et al.*, 2019). Furthermore, possible implications in the

treatment of infections with multidrug-resistant strains of pathogens represent a possible direction for research (Rinaldi *et al.*, 2021; Cao *et al.*, 2024). Despite promising *in vitro* results, practical use is hindered by the need for strict chemotype control and phytotoxicity risks (Djordjevic *et al.*, 2021; Górska-Drabik *et al.*, 2024). Incorporating the oil into controlled delivery systems and biodegradable matrices enhances biosafety and resource recovery, matching circular economy goals (Pantić *et al.*, 2025; Santos *et al.*, 2019).

CONCLUSIONS

Building on these insights, the fundamental question that remains unanswered is: "How can the results obtained in the laboratory be transferred to actual clinical treatments so that the combination of *Satureja montana* essential oil and antibiotics effectively combats resistant infections without causing side effects?" Consequently, further *in vivo* studies are needed to confirm whether this synergy maintains its efficacy and safety in living organisms, both in the medical and zootechnical fields and in crop protection.

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