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REVIEW

Economic Botany of *Salvia officinalis* L. with Emphasis on Essential Oil

Ioana Crișan*

Department of Plant Cultivation—Botany, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine from Cluj-Napoca, Cluj-Napoca, Romania
*Corresponding Author: Ioana Crișan. Email: ioana.crisan@usamvcluj.ro

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ABSTRACT: *Salvia officinalis* (Lamiaceae), commonly called garden sage or Dalmatian sage, is an aromatic species native to the Mediterranean Basin and one of the oldest medicinal herbs. Culinary importance is well attested historically and has continued relevance for contemporary regional gastronomy, particularly in Europe. Traditionally, it has been used for medicinal infusions, to flavor or preserve meat, and in the production of cheese specialties. Today, it is recognized for its commercial and industrial value. This work aims to provide an up-to-date look at the economic botany of this species, with special reference to the essential oil (EO) properties and its modern uses. The EO is produced by glandular trichomes that cover the plant and is rich in active compounds. The composition is dominated by oxygenated monoterpenes. Composition is variable depending on several natural or technological factors. The core EO profile is defined by major components such as α- and β-thujone, camphor, and 1,8-cineole in different proportions according to chemotype. Out of these, thujone is subject to limits due to safety concerns that must be considered across EO applications. Bioactivities such as antimicrobial, antioxidant, pharmacological potential, and pesticidal activity are well documented and fundamental to its diverse modern uses. EO finds wide applications in the food and beverage industry, as an animal feed additive and in several non-food uses. Flavoring, functional beverages, preservation of foodstuffs, and cosmetics remain the main destinations of use for EO and the most intensive areas of research. Novel findings explore the synergistic effect of *S. officinalis* EO with other EOs and optimized extraction and delivery systems. Traditional uses and current applications highlight the relevance of this species across historical and modern contexts.

KEYWORDS: Phytochemistry; terpenoids; ethnobotany; medicinal plant; leaf; culinary; genotype; chemotype

1 Introduction

Essential oils (EOs) are plant-derived products situated at the intersection of botany, tradition, chemistry, and modern applications. It has been estimated that from about 3000 EOs known, around 150 are of commercial importance and traded on the world markets [1]. Demand for EOs comes from the food and beverage market (35%), fragrance, cosmetics, and aromatherapy (29%), household goods (16%), and the pharmaceutical sector (15%), indicative of the main destinations of use [2,3]. Europe retains the largest share of the global EO market, followed by Asia Pacific and North America [3].

A market study published in 2025 on sage EO trends indicates that *Salvia* sp. EO market (*S. officinalis* as one of the main species) was valued at USD 7.83 billion in 2024 and is expected to reach USD 10.38 billion by 2030. The major challenges to the supply chain of raw material are related to environmental dependency, with major producing countries such as Spain, France, and Turkey registering a 15–20% decline in a recent report due to these factors. The high demand for organically certified sage is reflecting the consumer preferences [4].

There is an amplified interest in the use of EOs across a range of applications due to consumer behavior that favors naturally derived components across most everyday goods, from food and medicine to cosmetics [1]. EOs are intensely researched in relation to health and for naturally support to the immune system in pathological processes [5]. Due to the increased popularity in EO use and self-care practices based on plants, there is a need for examining evidence regarding the safety of administration and discerning between the quality and properties of EOs [6]. Therefore, what is currently needed is a meaningful contextualization of aromatic plant species used for EO production that follows the plant to its uses, from botany to applications.

Economic botany is a field of science that looks at plant species through the lens of plant-human interaction. It integrates botanical traits, phytochemical composition, and documented uses in both historical and modern contexts to understand plant species from the perspective of human use. This perspective places plants within both cultural and scientific frames of reference by connecting structural characteristics and chemical attributes with useful purposes. In this regard, *S. officinalis* is an especially appropriate case study of this field of science due to its long history of culinary and medicinal applications, which demonstrate a continuous plant-human relationship spanning centuries. This approach offers a logical framework for understanding how current scientific research on its EO converges with traditional knowledge.

S. officinalis is the most economically important species of the genus *Salvia*. It is a perennial aromatic plant used worldwide as a culinary herb and for medicinal purposes [7]. It has one of the oldest histories of use among medicinal plants [8]. It is especially a valuable industrial crop source of EO with various applications in the pharmaceutical and food industries and perfumery [9]. Demonstrated bioactivities are sustaining the wide range of modern uses [8]. As one of the most well-historically documented aromatic plants in Europe, its continued use reflects its cultural and functional relevance. Unlike many other medicinal and aromatic plants, *S. officinalis* bridges medicinal, culinary, ornamental, and applied uses.

The existing literature addresses this species from various perspectives ranging from agronomic to pharmacological, but few integrate ethnobotanical context, chemical composition, bioactivity, and application in the same framework for an updated view. This work invites the reader to an economic botany perspective that allows these dimensions to be examined together. The aim of this review is to provide a current view on *S. officinalis*, from botany to EO and its uses, illustrating the importance of this old herb in the current context, emphasizing its evolving relevance and future research directions.

2 History and Botany

2.1 History and Importance

The etymology of *S. officinalis* comes from the Latin "salvare," meaning "to cure" [10] and "officinalis," which literally means "of or belonging to an officīna" in reference to the storeroom of a monastery, where different necessaries, including medicines, were kept [11]. Sage has been an important medicinal plant since ancient times. It was attributed both medicinal potential and the power to dispel evil [12]. Sage is mentioned in the Ebers Papyrus (1500 BC) as a plant used for the treatment of itching in Ancient Egypt [13]. Theophrastus mentions a cultivated sage he called "elelisphakos," about which Pliny the Elder mentions it was also called "salvia" by the Romans. Further ancient specification mentions the mint-like scent and aromatic properties for which it was cultivated for medicinal use. It has been established that these ancient authors most likely referred to *S. officinalis* in their writings. Later on, the monastery gardens from Medieval times also cultivated the plant. The famous saying "*Cur moriatur homo cui Salvia crescit in horto*?" meaning

"Why would a man die whilst sage grows in the garden?" is found in different variants both in Italian and Anglo-Saxon manuscripts, as well as later English proverbs [12].

Commonly called Dalmatian sage, the native distribution of *S. officinalis* is limited to the Western part of the Balkan Peninsula, Greece, and Northern Italy, but it is naturalized in various parts of the Southern Europe. Furthermore, *S. officinalis* can be found throughout Europe as a medicinal, culinary, and ornamental herb, possibly introduced Europe-wide by Ancient Romans or later by monks during medieval times [12]. It was introduced in North America during the 17th century [14].

The leaves of *S. officinalis* have been used in Mediterranean cuisine as flavoring [15], particularly in Italy to this day [16,17], where it is used as a defining aromatic component in classic preparations such as saltimbocca [18]. However, archaeobotanical evidence indicates its established use for food in past centuries as far north as Finland [19]. The savory, slightly peppery flavor has sustained the use of *S. officinalis* in meat-based dishes and cold green sauces ("cold sage sauce") in early French cuisine [20]. Its use is attested as a cuisine ingredient at least since the late medieval period, according to its mentioning in the historical recipe book "Le Viandier de Taillevent" [21], which reflects the early integration of *S. officinalis* into European gastronomy. In English gastronomy, *S. officinalis* is used to achieve the distinctive flavor of Lincolnshire sausage [22], and in the production process of Sage Derby cheese, a variety of British Derby cheese, which is infused with sage to obtain a green marble effect and to confer subtle herbal flavor [23].

The medicinal uses of *S. officinalis* leaves and EO have been well documented, with consistent evidence for both traditional and current uses. At first used for medicinal properties by ancient Egyptians, then Greeks and Romans, eventually finding its way into traditional Unani, Indian Ayurvedic, and Siddha medicine [14], some of the common medicinal uses are summarized in Table 1.

Table 1: Traditional medicinal uses of *S. officinalis* [14].

Effect or Symptom Treated	Application
Oral infections and irritation, pharyngeal inflammations (stomatitis, gingivitis, pharyngitis)	gargle, mouthwash
Digestive disorders (dyspepsia, flatulence, bloating)	herbal tea, tincture
Excessive perspiration (hyperhidrosis, night sweats, menopause)	oral preparations
Skin wounds and minor inflammations	compresses (dressings), topical rinses
Cognitive support (memory, tonic use)	oral intake

The plants have biologically active compounds that are able to enter into complex interactions. However, the overall therapeutic effect comes from the synergy of multiple effects the plant components have together on the function of organs and systems within the human body [24]. Medicinal uses of *S. officinalis* have most often addressed symptoms of various mouth and throat disorders, digestive complaints, and some skin issues. As for the mode of application, the preparations relied on the release of active substances in infusions, extracts included in other preparations, and tinctures administered to the patient internally and externally. The plant has recognized carminative, antispasmodic, antiseptic, astringent, and antihidrotic properties [14].

2.2 Botanic Description

The genus *Salvia* comprises 1024 accepted species belonging to the family Lamiaceae [25]. A botanical family of huge economic importance [26]. In recent years, the genus *Salvia* has been circumscribed the small genera *Meriandra, Perovskia, Rosmarinus,* and *Zhumeria* [27]. Staminal morphology is a characteristic and distinctive feature of the genus *Salvia* [28]. Out of the large number of species from this genus, more than 150 species are cultivated for ornamental and medicinal purposes today [29]. A recent global synthesis of literature documented ethnobotanical evidence for the use of 187 *Salvia* species [30]. Despite the large number of species in this genus, only a few species are recognized as medicinal drug sources; other species exhibit undesired aroma or potentially harmful compounds [8]. By far, one of the most commonly cultivated is *S. officinalis* [10]. Besides *S. officinalis*, the species *S. sclarea*, *S. fructicosa*, *S. miltiorrhiza*, and *S. lavandulifolia* are included in reference monographs such as European Pharmacopoeia, in recognition of their established medicinal use and importance [31].

S. officinalis botanic characteristics can be observed in Fig. 1a–f. The species is an evergreen shrub, reaching 60–80 cm at maturity and spreading around about 1 m [32]. Life form is a chamaephyte [33]. The leaves are oblong-ovate to elliptical in shape, having a length of 2–10 cm and a width of 1–2 cm, with a finely crenate margin. The leaf tip is rounded or subacute [31]. The adaxial leaves surface is grey-green and whitish on the underside. Both sides of the leaf are covered with hairs. Flowers form on short pedicels and are arranged in verticillasters, with 4–20 whorls of flowers per inflorescence. Individual blooms are up to 2.5 cm long. Flowers are violet or purple in wild genotypes, but also white and pink flowers occur in cultivated varieties. The flowers last from early to late summer, but the main interest is the foliage [32]. The flower calyx is synsepalous, the corolla is sympetalous, the two stamens are adnate to the corolla tube, and the gynoecium is syncarpous with 2 carpels and a superior ovary. Nectaries are present. The fruit is a schizocarp consisting of 4 nutlets [34]. Pollination is entomophilous [29], and it is recognized as a good melliferous plant [35].

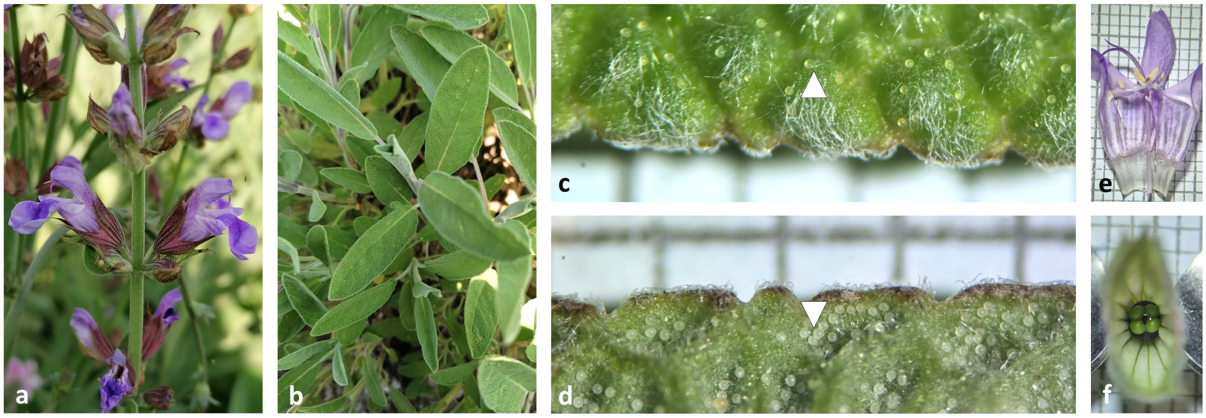

Figure 1: *Salvia officinalis*: inflorescence (**a**), leaves (**b**), adaxial leaf surface with secretory trichomes indicated by arrow (**c**), abaxial leaf surface with secretory trichomes indicated by arrow (**d**), flower with lever-stamen typical for the genus (**e**), schizocarp fruit—formation of the four nutlets (**f**). (original, photos c-f on millimeter paper).

Micromorphological examination indicates the presence of numerous protective trichomes articulated and bent with narrow elongated cells and a base cell with very thick walls, while the epidermis is presenting diacytic stomatal complexes [31]. Examination of secretory structures revealed the presence of peltate trichomes, which are characteristic of this botanic family, but in addition, four types of capitate glandular trichomes were also described in this species [36]. Study showed that density of peltate glandular trichomes, which are the most important ones for EO production in *S. officinalis*, can vary according to the physiological state of the plant, treatments, and localization (base, middle, tip of the leaf), but values on adaxial leaf surface ranged between less than 20 per mm^2 to over 50 per mm^2 [37,38]. The botanic characteristics are diagnostic pharmacognostic features important for accurate identification and safe medicinal use.

The major compounds in the plant (flowers, leaves, and stem) include alkaloids, carbohydrates (such as arabinose, galactose, glucose, mannose, xylose), fatty acids, glycosidic derivatives, phenolics, polyacetylenes, waxes, terpenes, and terpenoids (linalool, α-pinene, cineole, bornyl acetate, camphene, camphor, humulene, limonene, and thujone). Most of the compounds characterized from this species have been identified and isolated from the EO, alcohol/aqueous extract (rich in flavonoids), and plant infusion [39]. The aromatic characteristics are given by the volatile compounds such as α-pinene, β-pinene, camphene, β-myrcene, 1,8-cineole, α-thujone, β-thujone, camphor, and *trans*-caryophyllene [40].

The Botanic Garden Conservation International (BGCI) public database lists 60 genotypes (a number of subspecies, cultivars, and hybrids) of *S. officinalis* as part of living collections in botanic gardens (216 *ex situ* sites worldwide), with more than half of these represented by botanic gardens located in Europe [41]. Botanic gardens are important germplasm sources in preserving the genetic diversity of this species.

As evidence for the high interest in cultivating *S. officinalis* plants with exceptional characteristics, there are several cultivar categories based on the chromatic aspect of the plant or extractive properties:

- cultivars with grey-green leaves are the most listed by nurseries for commercial purposes, with particular interest for the broad-leaf genotypes that are preferred for culinary herb production and may exhibit reduced to absent flowering (due to selection): ‘Berggarten’ and ‘Herrenhausen’ [32];
- cultivars with grey-green leaves and ornamental white or pink flowers: ‘Albiflora’ and ‘Rosea’ [32];
- variegated cultivars: ‘Icterina’ a cultivar valued for green and gold patchy foliage [32], ‘Tricolor’ [42] a highly aromatic cultivar with variegated leaves displaying creamy borders;
- cultivars with bright golden foliage, such as ‘Kew Gold’ [42];
- purple-leaved cultivars: ‘Purpurascens’ [42] is one of the most grown cultivars and ‘Robin Hill’ that was further selected based on the first [32]
- cultivars suitable for EO production are: ‘Bona’, ‘Extrakta’ and ‘Nazareth’ [43];
- sterile hybrids such as ‘Regula’, ‘Newe Ya’ar’ and ‘No. 4’ [43].

The registration of new *Salvia* varieties is regulated by test guidelines, such as international harmonized ones established by the International Union for the Protection of New Varieties of Plants (UPOV), which defines criteria for Distinctness, Uniformity and Stability (DUS) applicable to the new varieties. For the genus *Salvia*, these guidelines are concerning all varieties and are not detailed per species. These provide morphological descriptors evaluated under controlled growing trials, such a plant growth habit and height, leaf blade morphology (shape, size, variegation, pubescence), inflorescence architecture, and corolla tube and lip characteristics and coloration. Particularly, specific group characteristics—such as growth habit, plant height, number of florets per node, and defined corolla color classes—are used to ensure consistent differentiation among varieties [44]. While these descriptors are particularly developed for ornamental types, they may also be applied to herbal forms, although additional characteristics may be required. Thus, varietal approval in *Salvia* is based on reproducible phenotypic traits rather than solely on phytochemical or functional parameters.

Breeding programs should integrate botanical characterization with EO profiling to contribute to the creation of cultivars tailored to specific aromatic and functional applications. This approach is one currently sought for medicinal plants in general [45]. Traditional breeding of *S. officinalis* uses wild populations as well as cultivars, focusing on traits of interest such as ornamental, secondary compound production, and tolerance to environmental factors. Molecular-assisted breeding for this species is relatively recent, but as a highly versatile and promising approach it may be a viable approach to address contemporary breeding objectives [43,46]. To date, breeding approaches targeting chemotype stabilization and EO yield remain vastly underexplored in this plant species. But, a preliminary study on induced polyploidy indicates that genome duplication in *S. officinalis* alters specialized metabolite patterns [47]. Therefore, it may represent a promising route for further investigation of possible effects on EO biosynthesis as well, and this should be considered in future research.

3 Essential Oil Composition and Variation

3.1 Composition

EO is one of the most economically important products obtained from the sage plants. The dried plants have up to about 3% EO [48]. Whole dried leaves of *S. officinalis* contain a minimum of 12 mL/kg of EO, while cut dried leaves contain at least 10 mL/kg assessed on an anhydrous basis [14]. EO is colorless to yellow, having a characteristic camphorate scent with spicy notes and a sharp, bitter taste [49]. The EO is dominated by oxygenated monoterpenes as major components (Table 2).

Table 2: Standard characteristics of the main components of *S. officinalis* leaves essential oil.

Class	Functional Group	Compound	Sensory	Standard Content Minimum–Maximum[1] [49]
Monoterpene hydrocarbons	alkene	α-pinene	turpentine-like [50], fir needle like [48]	1–6.5%
		camphene	camphor-like, insipid [51]	1.5–7%
		limonene	lemon-like [52]	0.5–3%
Oxygenated monoterpenes	ether	1,8-cineole (eucalyptol)	spicy cooling taste [53], eucalyptus-like [48]	5.5–13%
	ketone	α-thujone	herb-like [48]	18–43%
		β-thujone	herb-like [48]	3–8.5%
		camphor	mothball-like, strong [54]	4.5–24.5
	alcohol	linalool	flowery-fresh [55], citrusy [48]	<1%
	ester	linalyl acetate	floral-fruity [56]	
		bornyl acetate	sweet, woody, fresh like pine needles [57]	<2.5%
Sesquiterpene hydrocarbons	alkene	α-humulene	sweet, woody [58]	<12%

[1] Composition according to ISO 9909: 1997.

Besides *S. officinalis*, other commercially-important *Salvia* species are listed in officinal monographs, in regards with EO extraction, namely: *S. lavandulifolia*, *S. fruticosa*, and *S. sclarea*. However, out of these three, the composition volatile profile standards are given only for *S. lavandulifolia* and *S. sclarea*. Comparatively, EO of *S. officinalis* is characterized by higher proportions of α- and β-thujone (together often exceeding 20%), presence of moderate levels of camphor and 1,8-cineole. By contrast, *S. sclarea* exhibits a rather different profile dominated by linalyl acetate (56–78%) and linalool (6.5–24%), while thujone is restricted to trace levels ($\leq$0.2%), and the characteristic compound sclareol. *S. lavandulifolia* presents an intermediate pattern, typically containing higher levels of camphor and 1,8-cineole, while thujone remains limited to low thresholds ($\leq$0.5%). These standardized differences indicate that, despite the taxonomic proximity, the economically relevant volatile signatures of these species are relatively distinct, corresponding to different sensory attributes, subject to different safety considerations and industrial applications [31].

The functional groups of the EO components are related to the biological activities and sensory effects. These aspects are widely considered in the recommended uses for EO products. The aromatic profile of ketones (such as camphor) and ethers (such as 1,8 cineole) is associated with a sensation of clear airways. Whereas alcohols (such as linalool) have cleansing properties, while esters have soothing effects [59].

The major compounds of *S. officinalis* EO are thujone, camphor, and 1,8 cineole. According to Table 3, it can be observed that the most reported chemotypes across consulted studies were thujone-rich, corresponding to EOs from Serbia, Romania, and Turkey. Some cineole-rich EOs were obtained in Jordan and Syria, and camphor-dominated in Algeria, Egypt, and Tunisia.

Table 3: Composition for various provenances of *S. officinalis* essential oil.

Country	Source and Plant Raw Material[1]	No. of Compounds Identified	Major Components[2]	Source[3]
Algeria	ruderal (*herba*)	48	camphor 20.4%, α-thujone 19.6%, 1,8-cineole 12.3%, β-thujone 8%, viridiflorol 8%	[60]
Brazil	cultivated (*folium*)	47	α-thujone 40.9%, camphor 26.12%, α-pinene 5.85%, β-thujone 5.62%	[61]
Croatia	wild (*herba*)	25	α-thujone 12.6 to 42.6%, camphor 12.4 to 33.3%, 1,8-cineole 7.2 to 9.9%, camphene 5 to 7.4%, β-thujone 6.7 to 13.8%, borneol 5.7%, viridiflorol 5.2 to 9.3%	[62]
Egypt	cultivated (*herba*)	31	camphor 26.38%, 1,8-cineole 17.83%, α-thujone 13.82%, β-thujone 5.96%, manoyl oxide 5.46%	[63]
Estonia	cultivated (*herba*)	34	α-thujone 24.1%, camphor 16.4%, 1,8-cineole 11.7%, α-pinene 6.4%, α-humulene 6.4%, camphene 5.5%, β-thujone 5.2%	[64]
India	cultivated (*herba*)	60	α-thujone 38.1 to 41%, camphor 9.3 to 22.1%, 1,8 cineole 7.3 to 13.8%, (*E*)-caryophyllene 5.9%, viridiflorol 5.1 to 5.6%, manool 5%	[65]
Iran	cultivated (*herba*)	42	α-thujone 41.48%, borneol 8.33%, 1,8 cineole 7.94%, β-thujone 6.75%, virdiflorol 5.85%	[66]
Italy	wild (*herba*)	46	camphor 16.16 to18.92%, 1,8-cineole 8.8 to 9.86%, β-pinene 9.14%, α-thujone 7.63 to 9.26%, camphene 6.27 to 8.08%	[67]
Jordan	wild (*herba*)	25	1,8-cineole 39.5 to 50.3%, camphor 8.8–25%, β-pinene 7.3%, *E*-β-caryophyllene 5.2 to 5.5%	[68]
Libya	wild (*herba*)	13	camphor 27.3%, thujone 24.3%, 1,8-cineole 16.5%, sabinene 8.2%	[69]

Table 3: *Cont.*

Country	Source and Plant Raw Material[1]	No. of Compounds Identified	Major Components[2]	Source[3]
Portugal	cultivated (*folium*)	55	α-thujone 25.5%, camphor 19.51%, α-humulene 7.46%, 1,8-cineole 6.47%, viridiflorol 6.29%	[70]
Morocco	wild (*herba*)	33	β-thujone 29.84%, 1,8-cineole 16.82%, camphor 9.14%, viridiflorol 9.92%, β-caryophyllene 5.20%	[71]
North Macedonia	native populations (*folium*)	51–63	camphor 13.15–25.91%, α-thujone 19.25–26.33%, 1,8 cineole 6.51–13.60%, α-humulene 5.21–7.34%, viridiflorol 7.99%, (*E*)-caryophyllene 5.33%	[72]
Romania	cultivated (*herba*)	29	α-thujone 34.28%, camphor 16.17%, α-pinene 7.75%, camphene 7.1%, β-thujone 5.44%	[73]
Serbia and Montenegro	wild (*folium*, *flos*)	55	α-thujone 15.79%, 1,8-cineole 12.09%, camphor 11.49%, viridiflorol 5.97%, manool 5.2%	[74]
Serbia	wild (*folium*)	29	α-thujone 43.2%, camphor 17.6%, 1,8 cineole 13.8%, β-thujone 5.6%	[75]
Serbia	cultivated (*folium*)	33	camphor 30.9 to 31.5%, *cis*-thujone 23.5 to 28.3%, 1,8-cineole 6.1 to 11%, camphene 5.4%	[75]
Syria	wild (*folium*)	30–45	1,8-cineole 55 to 62%, camphor 8 to 10%, β-pinene 5.2 to 6%, borneol 5%	[76]
Tunisia	wild (*folium*)	49	camphor 25.14%, α-thujone 18.83%, 1,8-cineole 14.14%, viridiflorol 7.98%	[77]
Turkey	cultivated (*folium*, *flos*)	16	β-thujone 34.59%, α-thujone 12.6%, camphor 10.09%, viridiflorol 6.24%, α-humulene 5.72%	[78]

[1] raw material name *folium*—leaf, *flos*—flowers, *herba*—plant; [2] the composition reports only major compounds found in concentration exceeding 5%; [3] only sources where the provenance was clearly stated were used (e.g., cultivated or harvested from spontaneous flora), research on commercial purchased material was not included as provenance cannot be ascertained.

A study that analyzed over 180 EOs of *S. officinalis* leaf reported in literature identified five major chemotypes, with the most common being α-thujone > camphor > 1,8-cineole [79]. *S. officinalis* EO chemotypes have been delimited also based on different proportions of α- and β-thujone (α/β 10:1, 1.5:1, and 1:10). Furthermore, different accessions can be placed in chemotypes with low (9%), middle (22–28%), and high (39–44%) thujone content [80]. An important study screened 25 populations of sage across Southeast Europe, out of which 17 were from Balkan countries. The EO yield varied between 0.25 and 3.48%. A variation in the composition of EO and 77 compounds was identified across populations [81].

3.2 Factors That Influence Variation

There have been identified various factors influencing the EO yield and composition; these can range from factors that exercise influence during plant growth (e.g., natural geographical conditions, cultivation technologies), plant biology (e.g., plant organ, growth stage at harvest), or post-harvest factors (such as drying or extraction method).

A study in conditions from Syria indicated that altitude exercised an influence on the occurrence of minor compounds such as sabinene, α-terpinene and terpinolene that were synthesized only in plants at higher altitudes. While the occurrence of major compounds was similar, there was a variation in their percentage between altitudes [76]. The plant organ has an influence on the accumulation and composition of EO. A study in Portugal showed that flowering parts had the lowest percentage of total thujones, but these were more abundant in stem and leaves. By contrast, the highest content of β-pinene was in the flowering part and the lowest in the stem and leaves [70]. A study in the conditions of Iran demonstrated that 1,8 cineole levels were lower at the vegetative stage and reached highest level at flowering, then decreased during fruit setting [82]. A study conducted on *S. officinalis* cultivated in pedo-climatic conditions from Morocco assessed the influence of phenophase (vegetative, beginning of flowering and full flowering) on EO composition and bioactivity. Out of the 47 compounds identified, a variation was identified for minor compounds, while the major compounds remained similar. Moreover, β-pinene was identified only at the beginning of flowering and full flowering [83]. These findings confirm that phenology is a major factor influencing EO composition.

In sage crops, various technological factors can influence the EO composition. A study showed that shading nets caused a decrease in monoterpene hydrocarbons but an increase of sesquiterpene hydrocarbons [75]. Study showed that in the semi-arid cold conditions of Southwestern Iran, chitosan foliar application compensated for the deficit irrigation and enhanced EO yield [9]. The optimized ranges of agronomic resources such as planting density and fertilizer application in *S. officinalis* can be adjusted to favor higher EO yields and major bioactive compound content [84].

The drying of plant material and the extraction method have an influence on EO obtained. A study compared EO yield from fresh *S. officinalis* plant versus dried for varying duration of time ranging between 1 and 4 weeks. Findings indicate that lower EO yield was obtained from fresh plant (0.16%), followed by the longest drying duration (0.18%). The highest EO yield of 0.28% was obtained from plant material slowly dried at 25°C for 2 weeks. However, some minor components were found only in fresh herb EO, such as butyl acetate, α-phellandrene, neral, α-cadinene and viridiflorol [7]. A study compared the composition of *S. officinalis* EO obtained through the classic hydrodistillation and microwave-assisted hydrodistillation, indicating differences in detectable composition but without fundamentally altering the core EO profile. Results suggest that the microwave-assisted method can extract trace constituents (such as globulol, phenylethyl alcohol, alloaromadendrene, linalyl acetate) that remained below the detection level in the EO obtained by the classic method. Furthermore, the microwave power level could be adjusted to enhance extraction efficiency of some components such as viridiflorol, verticiol and eucalyptol [85].

4 Bioactivity and Applications

4.1 Bioactivity of EO

4.1.1 Antimicrobial and Antioxidant Activities

EOs display antimicrobial and antioxidant activity that are valuable for applications from food preservation to medical uses in drug discovery and delivery.

A comparative assessment of the antimicrobial activity of *S. officinalis* EO using the disc diffusion method against some frequent human pathogen strains indicated inhibitory effects against *Klebsiella pneumoniae* and no inhibitory effect against *Pseudomonas aeruginosa.* The inhibition zone diameter against the *K. pneumoniae* standard strain (ATCC) was 9.3 mm and increased to 13.3 mm against a clinical isolate from urinary tract infection. Further complementary *in silico* approaches, revealed via molecular docking that selected EO components, such as 1,8-cineol, 1-dodecene, linalool, *cis*-thujone and camphor, could interact with protein targets, including DNA gyrase (PDB ID: 1KZN), penicillin-binding protein (PDB ID: 8GPW), and the quorum-sensing regulator LasR (PDB ID: 2UV0), which are involved in bacterial resistance [86]. A study compared the efficacy of *S. officinalis* EO (caryophyllene dominant) and its combination with conventional antibiotics against *Salmonella typhi* using the diagonal measurement of the n-way drug interactions method to determine the fractional inhibitory concentration (FIC). Results showed that EO alone had a moderate antibacterial capacity, of 1.25 mg/mL minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC). However, some combinations of the *S. officinalis* EO with antibiotics showed enhanced effects against *S. typhi* when compared to various other EOs and antibiotic combinations. The combination of *S. officinalis* EO with vancomycin (FIC = 0.77) and EO with piperacillin/tazobactam (FIC = 0.34) were the most notable [87]. The antibacterial properties of *S. officinalis* EO (α-thujone dominant) were assessed based on disc diffusion method against two common food-borne bacterial strains. Inhibition zone diameter was 15.66 mm for *Escherichia coli* and 12.66 mm for *Staphylococcus aureus*, whereas reference antibiotics had inhibition zone dimeters of >20 mm [88].

S. officinalis EO (1,8 cineole dominant) was tested for activity against human pathogenic yeast (*Candida* spp. and *Cryptococcus* spp.), fungi (*Aspergillus* spp.) and dermatophytes (*Epidermophyton* sp., *Trichophyton* sp. and *Microsporum* sp.). Results indicated that dermatophyte strains and a yeast were more responsive to EO, such as *Trichophyton rubrum*, *Epidermophyton floccosum* and *Cryptococcus neoformans* with an MIC of 0.64 μL/mL [68].

Antioxidant activity of *S. officinalis* EO (camphene dominant) was assessed by multiple assays indicating IC_{50} 0.97 mg/mL 2,2-Diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging activity assay, IC_{50} 0.28 mg/mL ABTS [2,2′-azinobis-(3-ethylbenzthiazolin-6-sulfonic acid)] (ABTS+) free radical scavenging activity, IC_{50} 0.05 mg/mL hydrogen peroxide radical scavenging assay (H_2O_2), and IC_{50} 0.86 mg/mL nitric oxide radical scavenging (NO·) [89]. The synergistic effect of EOs blends is particularly interesting to analyze. A study investigated the synergic potential of *S. officinalis* EO in a blend with oregano (*Origanum vulgare*) and cumin (*Cuminum cyminum*). Findings suggest that higher bioactivity (antioxidant and antimicrobial) at lower doses can be obtained by using synergism of EO blends, widening the possibility of use as condiments in small doses to enhance flavor and food preservation [90].

4.1.2 Pharmacologic and Immunomodulatory Potential

Anti-inflammatory and cytotoxic activities are insightful as preliminary investigations in the pharmacological relevance of EOs. These can further provide new approaches for the use of bioactive compounds to modulate cellular processes in various pathologies.

The cytotoxic effect of *S. officinalis* EO (camphene dominant) was assessed on cell lines MCF-7 (breast adenocarcinoma) and HeLa (cervical adenocarcinoma) by the colorimetric 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) assay. Results indicated that dose-dependent effect, but also a different response of the cell lines with an IC_{50} value of 8.92 μg/mL on the HeLa cell line and an IC_{50} of 3.12 μg/mL for MCF-7 [89]. The anti-inflammatory activity of *S. officinalis* EO (1,8 cineole dominant) was assessed in the mouse macrophage cell line Raw 264.7. The nitric oxide (NO), a pro-inflammatory marker, was measured indirectly by assessing nitrite accumulation in the culture supernatants following LPS stimulation. Results demonstrated a reduced nitrite production due to EO which was dose-dependent. The authors concluded that EO displayed strong anti-inflammatory potential [68]. Studies in animal models demonstrated *S. officinalis* EO may attenuate the systemic inflammatory responses induced by scorpion envenomation in heart, lungs and liver tissue [91].

4.1.3 Acaricidal and Insecticidal Activities

Biological pest control is an important domain of application for EOs; therefore, it is increasingly investigated as a more natural alternative to pest management.

S. officinalis EO demonstrated acaricidal activity against tomato russet mite (*Aculops lycopersici*), with an LC_{50} of 6.01 mL/L [92]. Insecticidal effect was demonstrated against important cereal grain pests, such as wheat weevil (*Rhyzopertha dominica*) with LC_{50} of 2.51 μL/L of air, and rice weevil (*Sitophilus oryzae*) with LC_{50} of 6.02 μL/L of air after 12 h of exposure. Molecular docking assay suggests that the insecticidal effect may be due to the inhibitor activity of key enzymes [93]. The application of EO as a plant-derived product is enjoying support, in part with the increased awareness of the potentially harmful effects of pesticides. Thus, is it fueling the search for natural alternatives that could reduce their use. In this sense, *S. officinalis* EO could be a promising direction for further research.

In the overview of bioactivity evidence for *S. officinalis* EO, it becomes evident that the most consistent body of data comes from *in vitro* studies. These are important in elucidating mechanisms and identifying the functional potential of EO. The next step towards applications would be validating these findings and preparing them for upscaling.

4.2 Safety of EO and Active Principles

Plant-derived products continue to attract support and EOs are particularly becoming more available and promoted to the wide public. However, their expanding use requires careful scientific consideration. In the context of their growing availability and interest.

S. officinalis EO was given GRAS (Generally Recognized As Safe) status in the USA in 1965 [94], which is maintained to this day, and listed as a flavoring agent or adjuvant [95]. Shortly later, in 1970, the Council of Europe included *S. officinalis* EO on the list of substances, spices and seasonings admissible for use [94]. Thujone (and its isomers) is the major plant bioactive component used for flavoring of foods and beverages [96], found in particular abundance in some *S. officinalis* EO chemotypes (Table 3). Today there are in place at the European level some limitations for thujone in the final products, as acknowledgement of its potential toxicity, which is considered dose-dependent [96]. The recommendation stipulates 6 mg of thujone as the daily maximum limit of exposure for humans due to toxicity [97]. Furthermore, compared to the ISO 9909:1997 standard *S. officinalis* EO profile components (Table 1), the Regulation (EU) 2025/1400 admits lower maximum levels for the α-thujone (maximum 27%), and for β-thujone (7%) for *S. officinalis* EO destined for use as an additive in the feed of animals [98].

4.3 Food-Related Uses

S. officinalis EO has attracted interest for its food preservation properties, particularly for highly perishable ones. EO obtained from *S. officinalis* filter tea processing dust was added in a quantity of 0.05 μL/g in fresh pork sausages that were free of chemical additives, to enhance their stability and safety during aerobic storage. The results indicated that the right quantity of EO can be used without a negative sensory impact [99]. The results are promising, considering that obtaining EO from a waste material and repurposing it for meat preservation is subscribing to circular economy principles. Another study demonstrated that *S. officinalis* EO can be used as a natural antimicrobial for beef tenderloin undergoing sous-vide processing, and in particular, reduces the ability of *Listeria monocytogenes* to withstand heat during this type of processing [100]. A study indicated that the addition of sage preparations (including EO) in kombucha fresh cheese contributed to a significant increase in antimicrobial activity against food-borne pathogens during 30 days of storage [101]. *S. officinalis* EO nano-liposomes can be employed to achieve delayed browning and suppress respiratory metabolism in *Agaricus bisporus*, therefore indicating effective applications in preserving edible fungi after harvest [102].

In the beverage industry, the EO of *S. officinalis* is used for the flavoring of alcoholic beverages and liqueurs [94]. Recent research focused rather on *S. officinalis* extracts in prospecting their potential for functionalized beverages [103,104]. There are some notable challenges related to the use of EOs for the food and beverage industry that are due to physico-chemical properties such as poor solubility in water, susceptibility to oxidation, undesired organoleptic effects, and volatility, which somewhat has limited their use. But further research in optimized methods of EO delivery systems can address these challenges [105].

Food packaging industry needs materials that display less polluting and higher preserving properties. Functionalized food packaging aims to prolong the shelf life of food products and contribute to the reduction of food waste. A study investigated the physical-mechanical, and bioactivity properties of composite films made of potato starch, Zedo gum, and *S. officinalis* EO. Results highlighted that *S. officinalis* EO can act as a natural antioxidant and barrier-enhancing agent in biodegradable food packaging materials [106]. *S. officinalis* EO incorporated in alginate films enhanced key properties by reducing moisture, increasing flexibility, and providing antioxidant activity. Furthermore, a synergistic effect was observed between EO and zinc oxide nanoparticles (ZnONPs) when added as additives to the film, hinting at promising applications for fruit and vegetable packaging [107].

S. officinalis EO can be used in the feed of animals, respecting safety regulatory levels [108]. A study analyzed the fortified hay substrate incubation medium with EO at gradient doses between 10 and 80 μg/mL to assess the *in vitro* goat rumen fermentation kinetics. Results suggested that EO influenced digestibility and methane production, with lower-level doses between 10 and 20 μg demonstrating the most beneficial effects [109]. Furthermore, *S. officinalis* EO added to the milk of weaning-stage Holstein calves demonstrated a complex positive immune system response and improvement of performance variables [110].

4.4 Non-Food Uses

EOs in cosmetics can optimize product proprieties preservation while enhancing the marketing image of the final product. EOs are frequently used in perfumes, skin, and haircare products [111]. At the level of the European Union, Regulation 1223/2009 mandates microbiological purity for cosmetics [112]. *S. officinalis* EO at 1.5% proved efficacy against microbial strains and promising activity as a broad-spectrum preservative agent for the cosmetic industry [113]. *S. officinalis* EO could be included in some preservative systems of cosmetic hydrogel formulations due to its antimicrobial activity [114]. *S. officinalis* EO can be used as an ingredient in hair care, such as EO blends for anti-dandruff shampoo [115,116]. Microencapsulation of EOs is a highly attractive area of research that relies on the bioactive properties. However, further attention is needed to the understanding of bio-functional activities in various cosmetic formulations, stability during storage (particularly the interaction with other ingredients), and release modulation [111].

The perfume industry uses *S. officinalis* EO in various functional perfumery compositions due to the pleasant, fresh herbaceous note. It is suitable for alcoholic and cosmetic perfumery. The EO was noted to have a slightly woody dry-out attribute due to the sesquiterpene hydrocarbons such as humulene and caryophyllene, as well as oxygenated sesquiterpenes including viridiflorol. It is appreciated in blends with lavandin, rosemary, citrus oils, and bois de rose. It has been used to achieve fresh notes in men toiletries: aldehydic perfume bases and colognes, fougère, chypre, and after-shave lotions [94]. One of the most widely used websites for perfume information is placing sage (*S. officinalis*) in the group of greens, herbs, and fougère, describing the perfume profile as "savory, aromatic culinary note, hazy, soft, and mildly peppery", with top brands having men and unisex fragrances with sage notes in their portfolios [117]. A recent study identified 35 odorants in the dried *S. officinalis* plant material by using solvent-assisted flavor evaporation (SAFE) and aroma extract dilution analysis (AEDA), including several identified for the first time [118]. Such insights into sensory profiles can aid in further inspiring novel volatiles that might extend sage use in the fragrance industry.

S. officinalis EO is not particularly recommended for aromatherapy [14], but has been prospected for this potential, as aromatherapy remains a major destination of use for many EOs in general. An aromatherapy single-blind study involving adult hospitalized patients concluded that inhalation of *S. officinalis* EO with high borneol content might be a complementary approach to increase the well-being of patients during hospitalization [119].

5 Perspective Synthesis, Knowledge Gaps and Future Directions

This conceptual framing examined *S. officinalis* through the lens of economic botany, following the trajectory of EO along an axis that integrates plant structure, chemistry, and safety considerations with the practical applications. The continuity of traditional use to the contemporary ones highlights how one plant species has retained its relevance across centuries due to the functional properties of its metabolites. Today, this resides in a wide range of applications, from food and cosmetic to medicinal, naming a few of the main ones. This trajectory from plant to uses is depicted in Fig. 2.

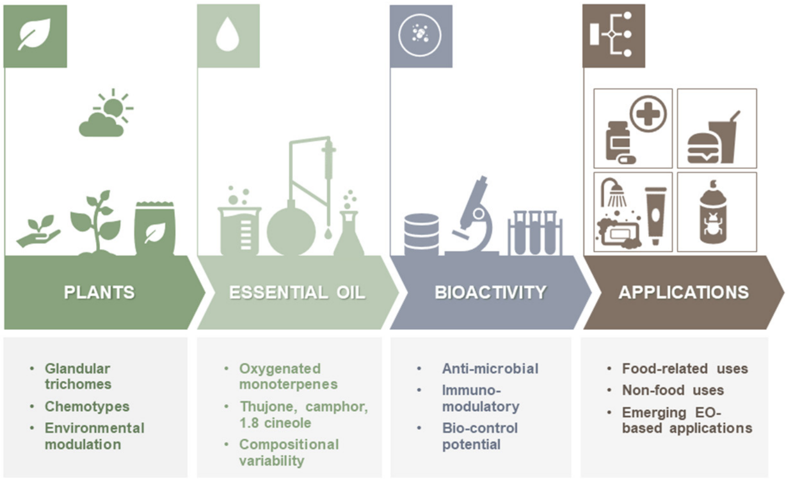

Figure 2: Economic botany as the functional axis between *S. officinalis* phytochemistry and the multi-sectoral trajectory of its volatile oils (original infographic).

The evidence presented in this work confirms the biological and practical values of *S. officinalis* EO. These arise from the convergence of several features: the presence and density of characteristic secretory structures, the distinct chemical profile dominated by oxygenated monoterpenes, and its long history of informed use that has continuity and diverged into current uses. There have been identified factors that may influence the composition of EO. Among these, geographic origin, cultivation conditions, and post-harvest handling and processing were shown to explain at least a part of the compositional variability for EO obtained. Despite this, core chemotypes, standardized approaches (such as precise moment of harvesting), ensure recognizable aromatic identity and functional properties of the EO obtained. However, the opportunities and challenges both arise from the balance between variability and compositional consistency. Regarding this last aspect, based on the examination of literature, several research gaps were identified that may need further elucidation to support optimization, diversified uses, and long-term industrial interest in this species. These aspects represent future research perspectives:

- The relationship between structure and function of the secretory tissue requires further integrated studies, as links between botanic features and agronomic outcomes are not fully elucidated, and literature is fragmented between morphometric data, anatomical features, yield, and chemical profiling;
- Chemotype-specificity should be better connected with application opportunities; there is currently a lack of comparative assessment of different chemotypes in relation with most suitable destination of use (e.g., bio-control, food, medicine), and the literature mostly does not go beyond safety thresholds (such as content of thujone) in expounding recommendations;
- There is a need for functional standardization, as current approaches in standardization address only the dominant compounds; in addition to this, a novel standardization based on the bioactivity outcomes would enable the development of a set of predictable application-oriented quality criteria;
- The breeding efforts could place greater emphasis on the selection for application-driven traits and crop resilience, which would ensure high-quality raw material and a stable supply chain for the industry.

6 Conclusion

Plant-derived products continue to attract support, and EOs are becoming more available and promoted to the wider public. As natural products, these benefit from an increased consumer interest. However, their expanding use requires careful scientific consideration. In the context of their growing availability and interest, this work provides an up-to-date overview of the properties, safety, and uses of EO from one of the most prized medicinal plants, *S. officinalis*.

S. officinalis is a medicinal and culinary plant with a distinct aroma conferred by the volatile oils produced at the level of microscopic secretory structures that cover the plant. The sage flavor is emblematic in European gastronomy: Italian saltimbocca, traditional French cold sage sauce, English Sage Derby cheese, and Lincolnshire sausage, indicating a continuity of historical culinary practice to contemporary food traditions.

Chemically, *S. officinalis* EO is dominated by oxygenated monoterpenes with thujone, camphor, and 1,8 cineole as major compounds. The composition varies with region, cultivation conditions, and post-harvest approaches to processing and extraction. These compositional features underpin the bioactivities of *S. officinalis* EO, which have become the basis for many of the modern food and non-food applications. The available evidence highlights antimicrobial and antioxidant activity, cytotoxic potential against cancer cell lines, and pesticidal activity against selected arthropods.

Accordingly, EO can be incorporated in food and beverages, as an additive in the feed of animals, and in biodegradable packaging. Furthermore, it can be added as natural ingredient in cosmetics or used for biological control of some pests.

Such applications point out the potential of EO, when used rationally, to reduce or complement the application of certain synthetic substances that have become a health concern of late. However, the destination of use is dependent on the composition of EO, which is variable, and on regulatory constraints that limit the levels of exposure to certain major compounds such as thujone. The existence of a natural variation and chemotypes remains a challenge in their standardized use. In this context, future research shall focus on the increased precision in botanical characterization, chemical profiling, and application-oriented research across its traditional and emerging domains.

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