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Orijinal araştırma (Original article)

Weed flora of cultivated sage (*Salvia officinalis* L. and *Salvia fruticosa* Mill.) in Türkiye

Türkiye'de yetiştirilen adaçayı (*Salvia officinalis* L. ve *Salvia fruticosa* Mill.) tarım alanlarının yabancı ot florası

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ABSTRACT

This study aimed to identify and characterize the weed flora associated with cultivated sage (*Salvia officinalis* L. and *S. fruticosa* Mill.) in Türkiye and to evaluate their diversity and distribution patterns. Understanding weed composition in sage fields is essential for developing sustainable management strategies in medicinal and aromatic plant production systems. The study was conducted in the Mediterranean region of Türkiye, covering sage cultivation areas in the provinces of Antalya, Muğla, and Denizli. Field surveys were carried out in 105 sage fields representing approximately 38 hectares. A systematic sampling method proportional to the field size was used to record weed species. Quantitative analyses included frequency (%) and density (plants/m²). Species richness and diversity were assessed using Simpson and Shannon diversity indices. NMDS, PERMANOVA, and RDA were applied to examine community differences and relationships with environmental variables. A total of 90 weed taxa were identified, comprising 77 dicotyledonous and 13 monocotyledonous species. The most species-rich families were Asteraceae (14 taxa), Poaceae (13 taxa), and Fabaceae (9 taxa). The dominant species were *Avena sterilis* L. (83%), *Convolvulus arvensis* L. (62%), and *Trifolium pratense* L. (60%). Weed diversity was higher in S. officinalis (79 taxa) than in *S. fruticosa* fields (47 taxa). RDA revealed significant correlations between weed distribution and altitude, soil organic carbon, pH, and texture. This study provides the first comprehensive assessment of weed vegetation in cultivated sage fields in Türkiye, offering valuable insights for integrated weed management and biodiversity conservation in medicinal and aromatic plant agroecosystems.

INTRODUCTION

Medicinal and aromatic plants (MAPs) are cultivated on relatively small areas worldwide and are therefore often classified as minor crops. Nevertheless, they have an important role in rural economies as well as in the pharmaceutical, food, cosmetic, and health industries. They are closely linked to cultural traditions, thereby contributing to both livelihoods and biodiversity (Božić et al. 2025). In Türkiye, MAPs have long held substantial cultural and economic importance due to the country's diverse geography, climatic conditions, and exceptional floristic richness, situated at the intersection of three major phytogeographical regions (Baytop 1999, Faydaoğlu and Sürücüoğlu 2011). Türkiye is among the leading suppliers of MAPs to the European Union, with approximately 500 species recorded, of which nearly 200 possess significant export potential (Pakdemirli et al. 2021). Currently, Türkiye exports MAPs to nearly 100 countries worldwide, with principal markets located in Europe, North and South America, the Middle and Far East, and North Africa. Major export commodities include thyme, bay leaf, cumin, anise, fennel, rosemary, licorice, mint, and lime; among these, sage also represents one of the most economically important medicinal and aromatic plants (Karık and Tunçtürk 2019).

Salvia is the most species-rich genus within the Lamiaceae family, comprising more than 1,000 taxa worldwide, of which approximately 115 occur naturally in Türkiye (Celep and Doğan 2023). Phylogenetically, the genus is polyphyletic and is classified into four major evolutionary lineages distributed across the Americas, Southwest Asia, North Asia, and East Asia (Walker and Sytsma 2007, Will and Classen-Bockhoff 2017). Salvia species are highly valued for their medicinal and aromatic properties because they contain a wide range of biologically active secondary metabolites, particularly terpenes and phenolic compounds with strong pharmacological effects (Ben Farhat et al. 2013, Zaman et al. 2022).

Although approximately 115 *Salvia* species are recorded in Türkiye, only two species, *S. officinalis* L. and *S. fruticosa* Mill. are cultivated commercially and possess the greatest economic significance (Tursun et al. 2021, Bayar et al. 2024). *S. officinalis* L. is primarily grown for essential oil production due to its complex composition of terpenes and phenolic derivatives (Durling et al. 2007, Athanasiadis et al. 2021), whereas *S. fruticosa* is widely consumed as an herbal tea and has long been used in traditional Anatolian medicine (Baytop 1999, Şenol et al. 2011, Bayar and Turgut 2021). Beyond Türkiye, sage cultivation is well established in several European countries, including Albania, Bulgaria, Croatia, Germany, Poland, Romania, Serbia, Montenegro, and Spain, as well as in the United States. Albania has traditionally been one of the world's leading producers, exporting approximately 1.500 tons of sage annually (BAKA 2020). In Türkiye, sage cultivation covered approximately 1.500 ha and yielded 2.329 tons in 2024 (TÜİK 2025).

Weeds are a major biotic constraint in sage cultivation, adversely affecting both crop productivity and product quality (Hou et al. 2024). The magnitude of weed interference depends on crop characteristics, management intensity, and local environmental conditions (Asín et al. 2013). Similar challenges have been reported in other medicinal and aromatic plants, particularly under organic farming production systems where synthetic herbicides are prohibited. For instance, large-scale surveys in Egypt revealed that weed composition varied with crop type and geographical location (Hendawy et al. 2019). Studies conducted in MAPs production systems have described weed species composition, life forms, and growth characteristics (Carrubba et al. 2009, Carrubba 2017). These studies showed that annual species account for approximately 75% of the weed flora, whereas biennial and perennial species together constitute the remaining 25%. Many of these weeds, such as *Amaranthus retroflexus* L., *Convolvulus arvensis* L., and *Chenopodium album* L., are common across a wide range of crops and environments. Life-form analyses revealed a predominance of therophytes, followed by hemicryptophytes and geophytes.

Crop management practices and weed control strategies also play a decisive role in shaping weed diversity. For example, field experiments in sweet basil (*Ocimum basilicum* L.) identified dominant weed species, including *Echinochloa colona* (L.) Link, *E. crus-galli* (L.) Beauv., *Dactyloctenium aegyptium* (L.) Will., *Eleusine indica* (L.) Gartner, *Caesulia axillaris* Rox., *Celosia argentea* L., and *Cyperus rotundus* L. (Giri et al. 2021). Similar to conventional field crops, weed infestations also represent a major constraint in the production of medicinal plants. A comprehensive survey in Serbia involving five medicinal crops-lemon balm, fennel, peppermint, ribwort plantain, and German chamomile-identified 109 weed taxa belonging to 29 botanical families, including both annual and perennial species occurring at high densities (Božić et al. 2025).

In sage cultivation, weeds can reduce yield and quality by competing for resources and contaminating harvested material (WHO 2003, Pala and Mennan 2022). In medicinal plants, contamination with toxic weeds poses an additional risk, as harmful secondary metabolites such as pyrrolizidine alkaloids (PAs) may unintentionally enter herbal raw materials (Çiğnitaş and Kitiş 2023). Therefore, determining weed species composition and density is critical for

developing effective and sustainable management strategies. Despite the increasing importance of sage cultivation, survey-based studies specifically addressing weed flora in cultivated sage are extremely limited.

The present study aimed to comprehensively characterize the weed flora associated with cultivated sage (*Salvia officinalis* L. and *S. fruticosa* Mill.) across the main production areas of Türkiye, quantify weed diversity and dominance patterns, and assess the relationships between weed community structure and key environmental factors. The findings provide a scientific basis for developing integrated, sustainable weed management strategies in sage production systems.

MATERIALS AND METHODS

Study area

The weed flora survey was conducted in sage (*S. officinalis* L. and *S. fruticosa* Mill.) cultivation areas located in three major production provinces of Türkiye: Denizli, Muğla, and Antalya (Figure 1). A representative view of a cultivated sage field in the study area is shown in Figure 2. In total, 105 commercial fields were surveyed, covering an overall area of 37.9 ha. The surveys were carried out from April to June 2021, before harvest, to identify weed species with the potential to contaminate the crop at harvest. The surveyed sites are characterized by a Mediterranean climate, with mild to hot summers and mild winters, and are situated at altitudes ranging from 61 to 1017 m above sea level.



Figure 1. Location of the study area in Türkiye



Figure 2. General view of cultivated sage (*S. officinalis*) field in the study area

Floristic and quantitative data

Surveys were conducted during the 2021 growing season using the systematic sampling method described by Bora and Karaca (1970), with the number of sampling points determined according to field size. Weed counts were performed using a 0.5 x 0.5 m quadrat. Data obtained from the surveys were evaluated using standard quantitative parameter frequency (%) calculated following the procedures described by [1] Odum and Barrett (1971). Weed density (plant/m^2) calculated with formula [2] (Sawicka et al. 2020). Weed biodiversity within the communities was estimated and compared based on Simpson Diversity İndex [3] (Simpson 1949), Shannon Diversity Index [4] (Shannon 1949), and Species Richness [5] (Simpson 1949). Species were identified using the "Flora of Türkiye" (Davis 1965), and life forms were classified according to the system of Christen C. Raunkiaer (1934).

$$FO = 100\,x\frac{n}{m} \qquad [1]$$

Where FO represents the frequency of occurrence, n indicates the number of fields where a given species was recorded, and m denotes the total number of fields surveyed.

$$L_{ch} = \frac{[L1 + L2 + L3 + L4 + \cdots]}{l_p + p_r} \qquad [2]$$

Where Lch refers to the average number of individuals of a species per square meter (plants/m^2). L1, L2, L3, and L4 correspond to counts from successive quadrat samples, lp represents the number of observations, and pr indicates the quadrat area (m^2).

$$\mathrm{D} = 1 - \left\{\frac{\sum \mathrm{n}i\,(\mathrm{n}i - 1)}{\mathrm{N}(\mathrm{N} - 1)}\right\} \qquad [3]$$

Where, D denotes the Simpson Diversity Index; ni expresses the density value of an individual species, while N refers to the total cumulative density of all species identified in the survey.

$$H' = -\sum_{i=1} pi\log(pi) \qquad [4]$$

Where, H′ corresponds to the Shannon Diversity Index, S represents the total number of species, and pi is the proportion of each species' density relative to the overall community density.

$$d1 = \frac{S - 1}{\log N} \qquad [5]$$

Where d1 indicates the species richness index, S is the total count of species, and N designates the overall density of all recorded species.

Beta-diversity and species composition

Differences in weed community composition among sites dominated by distinct *Salvia* species were examined using non-metric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarity. Ordination performance was evaluated using the stress coefficient. Additionally, permutational multivariate analysis of variance (PERMANOVA) with 999 random permutations was applied to assess statistically significant differences in species composition among the groups.

Relationship with environmental and soil variables

To examine the influence of climatic and edaphic factors on weed species composition, redundancy analysis (RDA) was applied. Environmental predictors included five-year annual means of relative humidity, temperature, and precipitation, together with soil variables including pH, sand, silt, clay, soil organic carbon, electrical conductivity, carbon stock, and altitude. Soil data for the survey coordinates were obtained from the Soil Fertilizer and Water Resources Central Research Institute, which provided standardized datasets for each field location. All environmental variables were standardized before analysis. The significance of RDA axes and environmental predictors was evaluated using permutation tests with 999 permutations. Significant variables were visualized using RDA biplots.

Data analysis and visualization

All survey data were compiled into a single dataset containing family, scientific species names, European and Mediterranean Plant Protection Organization (EPPO) codes, life forms, and province-level frequency (FO) and density (DE) values. Frequency values were classified into five percentage categories: class I (1–20%), class II (21–40%), class III (41–60%), class IV (61–80%), and class V (81–100%). Likewise, plant density was classified into five abundance intervals per square meter: D1 (<1 plant m^{-2}), D2 (1–5 plants m^{-2}), D3 (6–25 plants m^{-2}), D4 (26–100 plants m^{-2}), and D5 (>100 plants m^{-2}) (Božić et al. 2025).

Data processing and statistical analyses were performed in RStudio version 4.2.3 using the dplyr (version 1.1.4) (Wickham et al. 2023) and tidyr (version 1.3.1) packages (Wickham et al. 2024) (Core 2015). Visualization of weed flora distribution, including family-level richness, Raunkiaer's life form spectra, and province-averaged frequency and density heatmaps, was carried out using ggplot2 (version 3.5.1) (Wickham 2009). Diversity indices, RDA, NMDS, and PERMENOVA analysis were computed using the vegan package (version 2.6-4) in R (Oksanen et al. 2022).

RESULTS

Weed flora composition

A total of 90 distinct weed species were recorded across sage (*S. officinalis* L. and *S. fruticosa* Mill.) cultivation areas surveyed in Antalya, Muğla, and Denizli provinces. These species belonged to 29 families (Table 1). Among them, Asteraceae was the most species-rich, represented by 14 taxa, followed by Poaceae (13 taxa), Fabaceae (9 taxa), Brassicaceae (7 taxa), Apiaceae (5 taxa), Euphorbiaceae (4 taxa), and Geraniaceae (4 taxa) (Figure 5). The remaining families were represented by 1–3 species each, including Amaranthaceae (3 taxa), Lamiaceae (3 taxa), Malvaceae (3 taxa), Polygonaceae (2 taxa), Boraginaceae (2 taxa), Convolvulaceae (2 taxa), Papaveraceae (2 taxa) and Plantaginaceae (2 taxa), as well as one taxon each in Asparagaceae, Asphodelaceae, Caryophyllaceae, Caprifoliaceae, Hypericaceae, Portulacaceae, Primulaceae, Ranunculaceae, Resedaceae, Rubiaceae, Scrophulariaceae, Solanaceae, Urticaceae, and Zygophyllaceae.

Across provinces, 13 weed species exhibited either a mean frequency of occurrence greater than 20% or a mean density of at least 5 plants m^{-2}. Among these, only *Avena sterilis* L. and and *Glebionis segetum* (L.) Fourr. exceeded the density threshold, with mean densities of 6.0 and 9.5 plants m^{-2}, respectively. Species with mean frequencies above 20% included *A. sterilis* (56.4%), *Convolvulus arvensis* L. (44.0%), *Medicago orbicularis* (L.) Bartal. (41.1%), *G. segetum* (39.9%), *Trifolium pratense* L. (39.4%), *Lactuca serriola* L. (36.3%), *Bromus tectorum* L. (32.9%), *Anthemis arvensis* L. (32.9%), *Papaver rhoeas* L. (31.7%), *Leopoldia comosa* (L.) Parl. (28.2%), *Elymus repens* (L.) Gould (21.9%), *Rumex crispus* L. (21.9%), and *Hypericum* sp. (20.5%) (Figure 3).

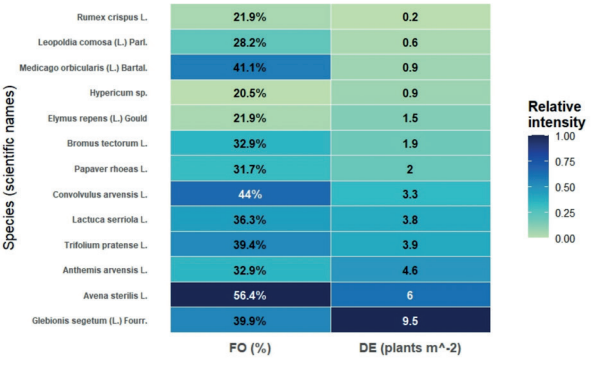


Figure 3. Average frequency (FO, %) and density (DE, plants m^{-2}) values of weed species recorded in sage (*Salvia officinalis* and *Salvia fruticosa* Mill) cultivation areas across three provinces (Antalya, Muğla, and Denizli). The heatmap highlights species with a frequency higher than 20% or density greater than 5 plants m^{-2}. FO values are expressed as percentages, while DE values represent the mean number of individuals per square meter

Table 1. Weed species identified in sage (*S. officinalis* and *S. fruticosa*) cultivation areas of Antalya, Muğla, and Denizli provinces, with their families, life forms, abundance (Ab.), and frequency (Fr.) values

Family	Scientific name	Life Form	S. fruticosa		S. officinalis		S. officinalis	
			Antalya		Muğla		Denizli	
			Ab.	Fr.	Ab.	Fr.	Ab.	Fr.
Amaranthaceae	*Chenopodium album* L.	T	D2	I	D1	I	D1	I
	Atriplex sp.	T	D1	I				
	Amaranthus retroflexus L.	T						
Apiaceae	*Tordylium apulum* L.	T	D1	II			D1	I
	Daucus carota L.	H			D2	I	D1	I
	Tragopogon sp.	H					D1	I
	Bifora radians M. Bieb.	T					D1	I
	Turgenia latifolia (L.) Hoffm.	T					D1	I
Asparagaceae	*Leopoldia comosa* (L.) Parl.	G	D1	II	D2	II	D1	I
Asphodelaceae	*Asphodelus aestivus* Brot.	G	D2	I				
Asteraceae	*Anthemis arvensis* L.	T	D2	III	D3	II	D1	I
	Sonchus asper (L.) Hill.	H	D2	I	D1	I	D1	I
	Taraxacum officinale Weber	H	D2	II	D1	I	D1	I
	Lactuca serriola L.	H	D3	III	D2	II	D1	I
	Matricaria sp.	T	D1	II	D1	I		
	Glebionis segetum (L.) Fourr.	T	D1	II	D4	II	D1	III
	Senecio vulgaris L.	T	D1	I			D1	I
	Silybum marianum (L.) Gaertn.	H	D2	I	D1	I	D1	I
	Calendula arvensis L.	T			D1	I		
	Achillea sp.	H					D1	I
	Centaurea cyanus L.	T					D1	I
	Conyza sp.	T					D1	I
	Xanthium strumarium L.	T					D1	I
	Centaurea solstitialis L.	T					D1	I
Berberidaceae	*Leontice leontopetalum* L.	G	D1	I			D1	I
Boraginaceae	*Heliotropium europaeum* L.	T					D1	I
	Anchusa sp.	T					D1	I
Brassicaceae	*Sinapis arvensis* L.	T	D3	II	D1	I	D1	I
	Capsella bursa-pastoris (L.)Medik.	T	D1	I			D1	I
	Raphanus raphanistrum L.	T	D1	II	D1	I	D1	I
	Alyssum alyssoides (L.) L.	T	D1	I			D1	I
	Lepidium draba L.	H			D1	I	D1	III
	Isatis tinctoria L.	T					D1	I
	Neslia paniculata (L.) Desv.	T					D1	I
Caprifoliaceae	*Lomelosia cretica* (L.) Greuter & Burdet	H					D1	I
Caryophyllaceae	*Cerastium dichotomum* L.	T	D1	I				
Convolvulaceae	*Convolvulus arvensis* L.	H	D3	III	D1	I	D2	IV
	Convolvulus galaticus Choisy.	H					D1	I

Euphorbiaceae	*Euphorbia peplus* L.	T	D1	I				
	Euphorbia helioscopia L.	T			D1	I	D1	I
	Mercurialis annua L.	T					D1	I
	Euphorbia sp.	T					D1	I
Fabaceae	*Trifolium pratense* L.	T	D3	III	D2	III	D1	I
	Medicago orbicularis (L.) Bartal.	T	D1	IV	D2	II	D1	I
	Medicago polymorpha L.	T	D1	I				
	Trifolium stellatum L.	T	D1	I	D2	I	D1	I
	Trifolium tomentosum L.	T		I				
	Vicia sativa L.	T	D2	I	D2	I	D1	I
	Lotus corniculatus L.	H			D2	II	D1	I
	Medicago lupina L.	T			D1	I		
	Onobrychis viciifolia Scop.	T					D1	I
Geraniaceae	*Erodium ciconium* (L.) L'Hér.	T			D1	I		
	Geranium pusillum L.	T			D1	I		
	Geranium sp.	T					D1	I
	Geranium dissectum L.	T					D1	I
Hypericaceae	*Hypericum* sp.	H	D2	III	D1	I	D1	I
Lamiaceae	*Lamium amplexicaule* L.	T	D1	I				
	Ajuga chamaepitys (L.) Schreb.	T	D1	I			D1	I
	Lamium purpureum L.	T	D3	I			D1	I
Malvaceae	*Malva neglecta* Wallr.	T	D1	II				
	Malva sylvestris L.	T/H	D1	II	D1	I		
	Alcea rosea L.	Ch					D1	I
Papaveraceae	*Papaver rhoeas* L.	T	D2	III	D1	II	D1	I
	Fumaria officinalis L.	T	D2	I	D1	I		
Plantaginaceae	*Veronica hederifolia* L.	T	D1	I				
	Plantago serraria L.	H			D1	I		
Poaceae	*Alopecurus myosuroides* Huds.	H	D3	III			D1	I
	Avena sterilis L.	T	D3	V	D3	III	D1	III
	Elymus repens (L.) Gould	H	D2	II	D2	I	D1	I
	Hordeum murinum L.	T	D1	I	D2	I	D1	I
	Lolium sp.	T	D1	I				
	Phalaris paradoxa L.	T	D1	I			D1	I
	Bromus tectorum L.	T	D1	I	D2	II	D1	III
	Hordeum vulgare L.	T	D1	I			D1	I
	Alopecurus pratensis L.	H			D1	I		
	Lolium temulentum L.	T			D1	I		
	Avena fatua L.	T					D1	I
	Sorghum halepense (L.) Pers.	H					D1	I
	Hordeum bulbosum L.	T					D1	I
Polygonaceae	*Rumex crispus* L.	G	D1	III	D1	I	D1	I
	Polygonum aviculare L.	T	D2	I	D1	II	D1	I
Portulacaceae	*Portulaca oleraceae* L.	T					D1	I

Primulaceae	*Anagallis arvensis* L.	T	D1	II	D2	I	D1	I
Ranunculaceae	*Adonis aestivalis* L.	T					D1	I
Resedaceae	*Reseda lutea* L.	H					D1	I
Rubiaceae	*Galium aparine* L.	T			D1	I	D1	I
Scrophulariaceae	*Verbascum pulverulentum* Vill.	H			D1	II	D1	I
Solanaceae	*Datura stramonium* L.	T					D1	I
Urticaceae	*Urtica urens* L.	T	D1	I				
Zygophyllaceae	*Tribulus terrestris* L.	T					D1	I

Ab. = abundance; Fr. = frequency; T = therophytes; T/H = thero-hemicryptophytes; G = geophytes; H = hemicryptophytes; Ch = chamaephytes. Abundance scale (D1-D5): D1 = <1 plant m^{-2}; D2 = 1-5 plants m^{-2}; D3 = 6-25 plants m^{-2}; D4 = 26-100 plants m^{-2}; D5 = >100 plants m^{-2}. Frequency scale (I-V): I = 1-20% of plots; II = 21-40%; III = 41-60%; IV = 61-80%; V = 81-100%.

Life-form spectrum

The analysis of life forms indicated a clear dominance of therophytes, represented by 65 species (72.2%). Hemicryptophytes accounted for 20 species (22.2%), followed by geophytes with 4 species (4.4%), and chamaephytes with 1 species (1.1%) (Figure 4).

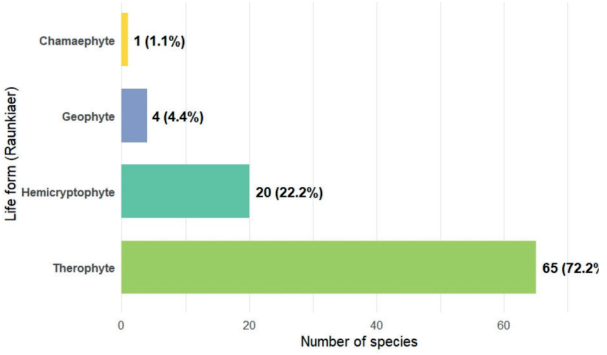


Figure 4. The participation of the life forms of weed flora in Raunkiaer's life forms in sage (*Salvia officinalis* and *Salvia fruticosa* cultivation areas)

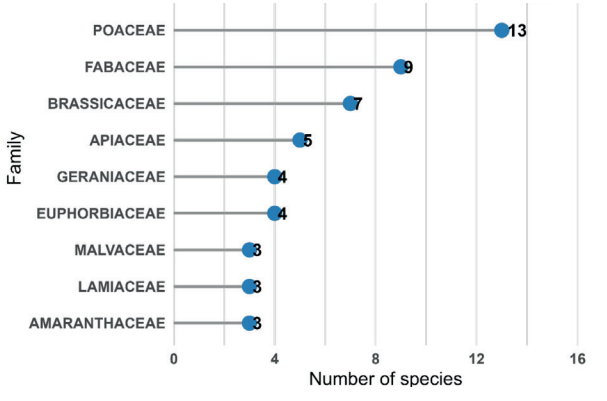


Figure 5. Number of weed species belonging to the most represented families in sage (*Salvia officinalis* and *Salvia fruticosa*) cultivation areas

Comparison of cumulative species richness revealed clear differences between the two sage species. A total of 79 weed species were recorded in *S. officinalis* cultivation fields, whereas 47 species were observed in *S. fruticosa* fields, indicating greater overall richness in *S. officinalis*. In contrast, *S. fruticosa* fields exhibited slightly higher Shannon diversity index (3.08) and Simpson index (0.93), indicating greater evenness in weed communities (Table 2). However, violin plot analysis of site-level richness showed that *S. fruticosa* sites generally hosted a greater number of weed species per sampling point than *S. officinalis* sites (Figure 6).

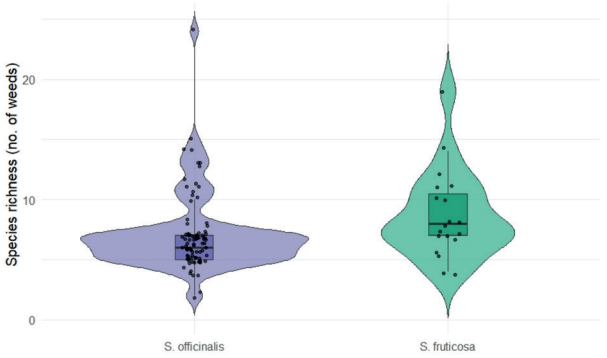


Figure 6. Violin plot illustrating the distribution of site-level weed species richness in *Salvia officinalis* and *Salvia fruticose* fields

In addition to differences in species richness, non-metric multidimensional scaling (NMDS) indicated clear compositional separation between weed communities associated with the two sage species. The stress value of 0.185 suggests a reliable ordination, and the separation of sites in the ordination space highlights distinct weed assemblages associated with each sage species (Figure 7).

Table 2. Diversity indices of weed communities associated with *S. officinalis* and *S. fruticosa*. Shannon and Simpson indices represent species diversity and evenness, while richness corresponds to the total number of species observed

Salvia Species	Shannon Diversity Index	Simpson Diversity Index	Richness
S. fruticosa	3.077	0.934	47
S. officinalis	2.910	0.886	79

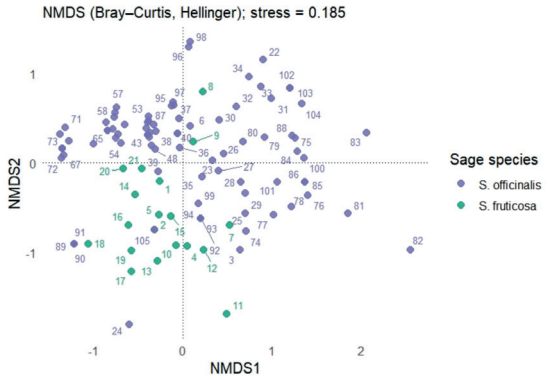


Figure 7. Non-metric multidimensional scaling (NMDS) ordination of weed community composition in *Salvia officinalis* and *Salvia fruticosa* sites (Bray-Curtis dissimilarity, Hellinger transformation). Each point represents a survey site, colored by sage species (Stress value = 0.185)

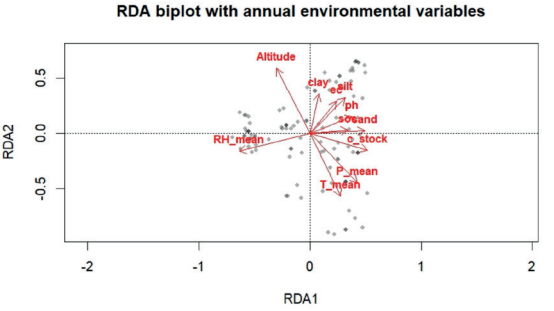


Figure 8. Redundancy analysis (RDA) biplot showing the relationship between weed species composition and environmental variables. Grey points represent survey sites, and red arrows indicate significant predictors. Arrow length and direction reflect the relative strength and orientation of environmental gradients

Abbreviations: RH_mean = mean relative humidity (%); T_mean = mean temperature (°C); P_mean = mean precipitation (mm=kg÷m²); SOC = soil organic carbon; EC = electrical conductivity

Environmental drivers of weed community composition

Redundancy analysis (RDA) demonstrated that weed species composition across the surveyed sage cultivation sites was significantly influenced by a combination of climatic and edaphic variables (overall model: F = 2.56, p = 0.001). The first two canonical axes (RDA1 and RDA2) accounted for the largest proportion of explained variation, with RDA1 explaining 8.4% (p = 0.001) and RDA2 explaining 3.7% (p = 0.002). Among the environmental predictors, altitude and mean annual relative humidity showed the strongest associations with species distribution patterns. Soil properties, including silt, clay and sand fractions, pH, soil organic carbon (SOC), and carbon stock, together with mean annual temperature and precipitation, also contributed significantly to the observed variation. The RDA biplot illustrates these relationships, with sites distributed along environmental gradients, indicating that both macroclimatic conditions and local soil characteristics jointly shaped weed community structure (Figure 8) (Athanasiadis et al. 2021).

DISCUSSION

Weed flora composition in cultivated sage fields reflects the combined influence of crop-specific management practices and broader ecological conditions. In the present study, the predominance of Asteraceae, Poaceae, and Fabaceae indicates that sage agroecosystems support a diverse weed community comparable to those reported in other perennial and medicinal crop systems. These results are consistent with previous weed surveys in Mediterranean cropping systems, where these families are often dominant due to their wide ecological amplitude and strong competitive ability (Leonti et al. 2006, Doğru and Kitiş 2023, Scavo et al. 2024, Eljebri et al. 2025). The high frequency of *A. sterilis*, *C. arvensis*, and *T. pratense* with the elevated densities of *G. segetum*, *A. myosuroides*, and *A. arvensis*, is in agreement with findings from studies on other aromatic and field crops throughout the Mediterranean basin (Šarić et al. 2011, Fanfarillo et al. 2020, Hammer and Szabó 2025). These weeds are known for their aggressive growth, persistence in seed banks, and significant impact on crop productivity.

Species richness and diversity indicated clear differences between the two sage species. *S. officinalis* fields hosted a greater number of total weed species, while *S. fruticosa* sites exhibited higher diversity and evenness, as reflected in the violin plot and Shannon–Wiener index results. This pattern may be explained by differences in canopy architecture, planting density, and microhabitat conditions, which can alter resource availability for weeds. Similar crop-dependent variations in weed communities have been observed in medicinal and aromatic plants such as lavender (Lengyel 2006), mint (Sokat 2019, Poudel 2022), thymus (Sokat 2021) and anise (Nemli et al. 2019). Collectively, these findings suggest that crop identity, in addition to environmental drivers, plays a central role in shaping weed assemblages. Our results are also consistent with those reported by Božić et al. (2025), who identified both perennial species, such as *E. repens*, *C. arvense*, and *C. arvensis* and annuals, including A. retro*flexus* and *C. album*, as dominant components of weed communities in medicinal crop systems in Serbia. Similar to their conclusions, the present RDA analysis demonstrated that soil and climatic parameters significantly shaped species distribution in sage fields. These findings underscore the importance of region-specific ecological factors in determining weed community dynamics in medicinal and aromatic plant production systems.

Ordination analyses (RDA) demonstrated that both climatic and soil variables significantly influenced weed community composition. Altitude, soil organic carbon, and mean annual temperature and precipitation were among the most important explanatory factors. This is consistent with previous studies showing that weed communities are structured not only by crop management but also by broader edaphic and climatic gradients (Fried et al. 2008, Rauber et al. 2021). Similar relationships between soil physicochemical properties and weed distribution have been reported in orchard systems, where canonical correspondence analyses revealed strong associations between weed density, soil texture, nutrient status, and altitude (Esitmez and Isik 2024). In another study, high altitude and soil organic carbon have been linked with increased weed diversity due to more heterogeneous resource distribution (Hyvönen and Salonen 2002). Conversely, extreme soil pH or salinity may act as strong filters, reducing species richness but favoring stress-tolerant weeds (Lososová et al. 2004).

From a management perspective, the dominance of annual grass weeds such as *A. sterilis* and *A. myosuroides* is of particular concern (Comont et al. 2024, Sasanfar et al. 2024). These species are among the most problematic weeds in Europe due to their competitive ability and herbicide resistance (Heap 2025). Their presence in sage fields highlights the need for integrated weed management (IWM) strategies incorporating crop rotation, mechanical control, and, where permitted, selective herbicides suitable for perennial aromatic crops. The occurrence of perennial weeds such as *Convolvulus arvensis* further complicates management, as their regenerative capacity through vegetative structures reduces the effectiveness of conventional control measures (Davis et al. 2018).

Overall, the present study demonstrates that sage fields in Türkiye host a diverse and complex weed flora shaped by both crop species and environmental gradients. These findings emphasize the necessity of developing integrated management approaches tailored to local soil and climatic conditions. Moreover, identifying indicator species linked to specific environmental factors provides valuable ecological insights that may contribute to more targeted and sustainable weed control (Bajwa et al. 2019).

To our knowledge, this study represents the first comprehensive survey of weed flora in cultivated sage fields in Türkiye. The results fill a significant knowledge gap and provide a robust baseline for further ecological, agronomic and weed management research in medicinal and aromatic crop production systems.

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ÖZET

Bu çalışma, Türkiye'de yetiştirilen adaçayı (*Salvia officinalis* L. ve *S. fruticosa* Mill.) ile ilişkili yabancı ot florasını tanımlamayı ve karakterize etmeyi, ayrıca çeşitlilik ve dağılım modellerini değerlendirmeyi amaçlamıştır. Adaçayı tarlalarındaki yabancı ot bileşimini anlamak, tıbbi ve aromatik bitki üretim sistemlerinde sürdürülebilir yönetim stratejileri geliştirmek için elzemdir. Çalışma, Türkiye'nin Akdeniz bölgesinde, Antalya, Muğla ve Denizli illerindeki adaçayı yetiştirme alanlarını kapsayacak şekilde gerçekleştirilmiştir. Yaklaşık 38 hektarlık bir alanı temsil eden 105 adaçayı tarlasında saha araştırmaları yapılmıştır. Yabancı ot türlerini kaydetmek için tarla büyüklüğüne orantılı sistematik bir örnekleme yöntemi kullanılmıştır. Kantitatif analizler arasında sıklık (%) ve yoğunluk (bitki/m^2) yer almıştır. Tür zenginliği ve çeşitliliği, Simpson ve

Shannon çeşitlilik indeksleri kullanılarak değerlendirilmiştir. Topluluk farklılıklarını ve çevresel değişkenlerle ilişkilerini incelemek için NMDS, PERMANOVA ve RDA yöntemleri uygulanmıştır. Toplam 90 yabancı ot taksonu tanımlandı; bunların 77'si çift çenekli, 13'ü tek çenekli türdü. En fazla tür içeren familyalar Asteraceae (14 takson), Poaceae (13 takson) ve Fabaceae (9 takson) idi. Baskın türler *Avena sterilis* L. (%83), *Convolvulus arvensis* L. (%62) ve *Trifolium pratense* L. (%60) idi. Yabancı ot çeşitliliği *S. officinalis* tarlalarında (79 takson) *S. fruticosa* tarlalarına (47 takson) göre daha yüksekti. RDA, yabancı ot dağılımı ile rakım, toprak organik karbonu, pH ve doku arasında anlamlı korelasyonlar ortaya koydu. Bu çalışma, Türkiye'deki ekili adaçayı tarlalarındaki yabancı ot bitki örtüsünün ilk kapsamlı değerlendirmesini sunarak, tıbbi ve aromatik bitki agroekosistemlerinde entegre yabancı ot yönetimi ve biyoçeşitlilik koruması için değerli bilgiler sağlamaktadır.

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