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Effects of Machine and Manual Harvesting on Some Quality Parameters and Operational Performance in Anatolian Sage (*Salvia fruticosa* Mill.)

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Abstract

Harvesting method significantly influences both product quality and operational efficiency in medicinal and aromatic plant production. This study comparatively evaluated manual and machine harvesting in *Salvia fruticosa* (Anatolian sage) cultivated under semi-arid continental conditions in Central Anatolia (Karaman, Türkiye). Plants were harvested at full flowering stage, and assessments included biomass yield, essential oil (EO) content and yield, EO composition, elemental composition, antioxidant activity, harvest losses, and field performance. Manual harvesting resulted in higher fresh and dry biomass yields (6670 and 2440 kg ha^{-1}) compared to machine harvesting (5800 and 2120 kg ha^{-1}). Essential oil content was significantly greater under manual harvesting (2.03%) than machine harvesting (1.57%) Manually harvested samples also showed higher concentrations of Ca, Zn, Cu, and B, whereas antioxidant activity did not differ significantly between treatments. Machine harvesting achieved substantially greater field capacity (0.315 ha h^{-1}) than manual harvesting (0.0114–0.0138 ha h^{-1}) but was associated with higher harvest losses (12.04% vs. 8.40%). Overall, results indicate a trade-off between operational efficiency and quality preservation, highlighting the need to optimize machine harvesting parameters for sustainable large-scale production.

Keywords: *Salvia fruticosa*; Anatolian sage; manual harvesting; machine harvesting; work efficiency; essential oil composition

1. Introduction

Medicinal and aromatic plants (MAPs) constitute strategic botanical resources for the global pharmaceutical, cosmetic, food, and functional product industries owing to their rich reservoir of secondary metabolites and bioactive constituents. The economic valuation of these crops is intrinsically linked to specific quality parameters, primarily essential oil (EO) yield, chemical composition, and antioxidant capacity. Within the Lamiaceae family, renowned for its high essential oil productivity, Anatolian sage (*Salvia fruticosa* Mill.; syn. *S. triloba* L.) stands out as a species of exceptional ecological adaptability and commercial relevance. *Salvia fruticosa* is widely known by several vernacular names across its distribution area. In Türkiye, it is commonly referred to as "Anadolu adaçayı", while in the international herbal trade it is often marketed as "Greek sage" or "East Mediterranean sage." The essential oil derived from this species is traditionally known in Türkiye as "elma yağı" or "acı elma yağı," a designation associated with its characteristic aroma and widespread ethnomedicinal use [1]. Traditionally, Anatolian sage essential oil has been employed as a carminative, antispasmodic, mild sedative, and digestive aid, particularly in the alleviation of gastrointestinal discomfort and infantile colic. These therapeutic properties are largely attributed to its high content of oxygenated monoterpenes, especially 1,8-cineole and camphor, which exhibit antimicrobial, anti-inflammatory, and smooth muscle–relaxant activities [2,3]. Although not endemic to Türkiye, *S. fruticosa* is a characteristic and dominant element of the Eastern Mediterranean flora, naturally distributed across Türkiye, Greece, Cyprus, Italy, Syria, Israel, and parts of North Africa.

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While Türkiye represents a major center of diversity for the genus *Salvia*, hosting numerous endemic taxa, *S. fruticosa* is distinguished not by endemicity but by its economic dominance. It remains one of the most commercially exploited sage species in the region and serves as a primary biological source for large-scale essential oil production [1–4]. Morphologically, *S. fruticosa* is a perennial, evergreen subshrub reaching 60–120 cm in height, characterized by quadrangular stems and grey-green, rugose leaves that are densely tomentose on the abaxial surface. The epithet "triloba" refers to its frequently trilobed leaves consisting of a prominent terminal lobe and two smaller basal lobes. Its verticillaster inflorescences bear bilabiate flowers ranging from lilac to violet-blue. In Türkiye, the species occurs predominantly along calcareous slopes and lithosols within Aegean and Mediterranean maquis ecosystems, extending from sea level to elevations of approximately 1000 m [4]. The essential oil of *S. fruticosa* is characterized by a predominance of oxygenated monoterpenes, particularly 1,8-cineole, camphor, and borneol, which largely determine its pharmacological and aromatic value. However, the biosynthesis and accumulation of these metabolites are highly plastic and depend on the complex interaction between genetic background, environmental conditions, and agronomic practices. Previous studies have demonstrated that environmental stress factors, harvest timing, and post-harvest handling significantly influence both 1,8-cineole concentration and total EO yield [3–5]. In MAP cultivation systems, harvesting represents a critical operational stage that directly determines biomass recovery, drug yield, and phytochemical integrity [6,7]. The glandular trichomes responsible for EO synthesis and storage are extremely susceptible to mechanical injury. Consequently, traditional production systems have relied predominantly on manual harvesting to minimize tissue disruption and preserve volatile compounds. Nevertheless, increasing global demand, rising labor costs, and narrowing harvest windows have driven producers toward mechanized harvesting systems. Mechanical harvesting enables rapid biomass collection across large production areas; however, it introduces stress factors such as vibration, impact, friction, and non-selective cutting. These factors may rupture glandular trichomes, promote premature volatilization, and alter essential oil composition prior to distillation [8]. In *S. fruticosa*, its major constituent 1,8-cineole has been reported to be particularly sensitive to harvesting and processing conditions [3]. Beyond essential oil parameters, harvesting strategy also affects biomass distribution, plant fraction ratios, and physiological responses. Mechanical intervention may act as a mild abiotic elicitor stimulating phenolic synthesis; however, excessive mechanical damage can reduce overall antioxidant capacity, as assessed by DPPH and FRAP assays [9,10]. Despite Türkiye's prominent position in the global sage market, comparative studies evaluating manual versus mechanized harvesting in *S. fruticosa*, particularly under the semi-arid transitional conditions of Central Anatolia, remain limited. The present study was conducted in the Göztepe region of Karaman (alt. ~1050 m), characterized by high solar irradiance, marked diurnal temperature variation, and low relative humidity—conditions conducive to secondary metabolite accumulation. Focusing exclusively on *Salvia fruticosa* (Anatolian sage), this study comprehensively evaluates the effects of manual and mechanical harvesting on pre- and post-harvest physical properties, macro- and micro-element contents, essential oil yield and composition, antioxidant activity, and overall harvest efficiency. In addition, the operational performance (work success and harvest efficiency) of both harvesting methods was determined. The findings aim to provide a scientific foundation for sustainable, energy-efficient, and quality-oriented mechanization strategies in medicinal plant production.

2. Results and Discussion

The results of the analyses conducted to evaluate the effects of harvesting methods on the morphological, yield, and quality parameters of *Salvia fruticosa* are discussed sequentially.

2.1. Some Pre- and Post-Harvest Physical Characteristics

The mean plant height, canopy diameter, and tillering count of the harvested plants were determined as 638.3 mm, 823.3 mm, and 53 branches, respectively. The mean fresh and dry herbage weights per plant were calculated as 600 g plant^{-1} and 220 g plant^{-1}, respectively. In manual

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harvesting, the average fresh and dry herbage yields were determined as 6670 kg ha^{-1} and 2440 kg ha^{-1}, respectively, whereas in mechanical harvesting, these values were found to be 5800 kg ha^{-1} and 2120 kg ha^{-1}. Post-harvest measurements revealed that the average stubble height was 223.3 mm for mechanical harvesting and 160 mm for manual harvesting. Regarding the post-harvest plant canopy diameter, the mean value was measured as 488.3 mm in mechanical harvesting, whereas it was 588.3 mm in manual harvesting. Since manual harvesting involved a lower cutting height (cutting closer to the ground) compared to mechanical harvesting, the biomass yield per unit area significantly increased. An evaluation of the harvest loss results revealed that the total loss rate in mechanical harvesting (12.04%) was approximately 50% higher than that of manual harvesting (8.40%). This significant increase is attributed to specific structural and operational parameters, including vibration generated during harvesting, machine forward speed, impact forces, and the inability of the fixed cutting height to fully adapt to the variable plant canopy architecture. These losses could potentially be mitigated through design modifications and adjustments to the machine. Particularly in *Salvia fruticosa* (syn. *S. triloba*), which exhibits a semi-woody and multi-branched morphology, losses are exacerbated by lower shoots remaining below the cutting line and biomass shedding (shattering) onto the ground during the operation. In contrast, manual harvesting significantly minimized biomass loss by enabling a more controlled and selective cutting process. Collectively, these findings demonstrate that while mechanical harvesting offers distinct advantages in terms of labor and time efficiency, it may result in trade-offs regarding biomass recovery and harvest efficiency, leading to potential losses in yield and quality.

The fresh biomass yields obtained in the present study (5800–6700 kg ha^{-1}) are in high alignment with the ranges previously reported for *Salvia fruticosa* cultivated under Mediterranean ecological conditions, which typically vary between 5500 and 8000 kg ha^{-1} [18]. The observed variations in biomass recovery and yield can be attributed to morphological variability, a phenomenon well-documented among Greek sage populations [19]. Furthermore, the higher yield recorded in manual harvesting in this study can be explained by the reduced cutting height, which has been shown to increase harvestable biomass per unit area in perennial Lamiaceae species. Conversely, the total losses observed in mechanical harvesting fall within the 8–15% range reported in various aromatic crops, where losses are predominantly influenced by forward speed and canopy heterogeneity [7].

2.2. Essential Oil Content(%) and Yield (kg/da)

The essential oil content and yield (kg ha^{-1}) of *Salvia fruticosa* obtained from both harvesting methods are given in Table 1. The experimental results revealed a significant reduction in essential oil (EO) content in machine harvested *Salvia fruticosa* plants (1.57%) compared to manually harvested ones (2.03%). Correspondingly, the essential oil yield was determined as 49.5 L ha^{-1} in manual harvesting, whereas it was recorded as 33.3 L ha^{-1} in mechanical harvesting. This substantial loss of approximately 22.6% can be primarily attributed to the physical rupture of fragile glandular trichomes caused by the intense vibration and friction of the reciprocating cutter bar, which leads to the immediate volatilization of sensitive monoterpenes before distillation. Furthermore, the non-selective nature of mechanical harvesting incorporates a larger proportion of woody stems compared to the selective cutting of tender, leaf-rich upper parts in manual harvesting, thereby diluting the overall oil percentage in the processed biomass. These findings suggest that while mechanization enhances operational speed, it introduces significant physical stress that compromises phytochemical integrity, aligning with reports of impact-induced losses in other *Lamiaceae* species [8]. The essential oil (EO) content obtained from manual harvesting (2.03%) falls within the typical range of 1.5–2.5% previously reported for *S. fruticosa* under Mediterranean ecological conditions [3–20]. This accumulation is known to be significantly influenced by various environmental and agronomic factors. The predominance of oxygenated monoterpenes such as 1,8-cineole in the present study is consistent with previous reports on Greek *Salvia fruticosa* populations [21]. Similar essential oil profiles characterized by high proportions of oxygenated monoterpenes, particularly 1,8-cineole and camphor, have also been reported in different *Salvia* species, including *S. fruticosa*, confirming the

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chemotypic consistency observed in Mediterranean sage populations [22]. However, a reduction in EO content was observed following mechanical harvesting. Such reductions in essential oil levels during mechanical handling have been attributed to the rupture of glandular trichomes and subsequent pre-distillation volatilization losses [8].

Table 1. Essential oil content (%) and yield (L ha^{-1}) of manually and machine-harvested *Salvia fruticosa.*

Harvesting Methods	Essential Oil Content (%)	Essential Oil Yield (L ha^{-1})
Manual Harvesting	2.03±0.15	49.5±0.37
Machine Harvesting	1.57±0.22	33.3±0.56

2.3. Essential Oil Composition (%)

In this study, the effects of machine and manual harvesting methods on the essential oil composition of *Salvia fruticosa* (syn. *S. triloba*) were comprehensively evaluated. The findings demonstrate that the harvesting method significantly influences not only the component ratios but also the distribution of chemical structures and the potential biological activity. The essential oil compositions obtained from manual and machine harvesting are given in Table 3 and Table 4, respectively.

In manually harvested samples, oxygenated monoterpenes constituted the dominant fraction of the essential oil, with particularly high concentrations of 1,8-cineole (43.07%) and camphor (20.12%). These compounds are low-molecular-weight, highly volatile structures stored in glandular trichomes. The preservation of cellular integrity and the minimization of mechanical damage to plant tissues and oil glands during manual harvesting likely facilitated the higher retention of these volatile and biologically active compounds. This preservation can be regarded as a quality indicator that enhances the therapeutic potential of the oil, particularly regarding oxygenated monoterpenes.

Conversely, a marked redistribution in the essential oil profile was observed in machine harvesting. While the proportion of 1,8-cineole decreased by nearly half (21.77%), monoterpene ketones such as thujone (19.94%) and (+)-2-bornanone (16.12%) showed a significant increase. The physical stress, tissue bruising, and potential heat generation induced by mechanical harvesting may have led to both volatile losses and the modification of secondary metabolic pathways. It is well established that mechanical stress in plants triggers jasmonate-mediated defense responses and activates specific terpene biosynthesis pathways. The increase in ketone-structured defense metabolites, such as thujone, may be associated with this stress response.

Moreover, the relative abundance of the sesquiterpene fraction (e.g., caryophyllene 5.22% and viridiflorol 5.84%) was found to be higher in machine harvested samples. Sesquiterpenes are compounds with higher molecular weights and lower volatility. The proportional increase in these more stable sesquiterpenes is likely a consequence of the partial loss or volatilization of the lighter monoterpenes, shifting the chemical profile towards a "heavier" and less volatile character.

From a chemical structure perspective, manually harvested samples were characterized by a higher content of oxygenated monoterpenes, whereas mechanically harvested samples showed a predominance of ketone derivatives and sesquiterpenes. Pharmacologically, the high levels of 1,8-cineole and camphor in manual harvesting are favorable traits for anti-inflammatory, mucolytic, and antimicrobial potential. In contrast, the increase in thujone content requires careful consideration regarding quality standardization due to its neuroactive and potentially toxic effects at high doses. Türkmen (2021) [22] similarly reported that *Salvia fruticosa* essential oil is predominantly composed of oxygenated monoterpenes, with 1,8-cineole and camphor representing the major constituents, supporting the compositional pattern observed in the current investigation. The predominance of 1,8-cineole and camphor in manually harvested samples is highly consistent with the established chemotypes of *S. fruticosa* previously described in Mediterranean populations [3–18]. However, the chemical shifts observed in mechanically harvested plants, particularly the increase in ketone derivatives like thujone, suggest a physiological response to harvesting-induced trauma. Mechanical

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stress and tissue wounding are known to activate jasmonate-mediated secondary metabolic pathways, which serve as a primary defense mechanism in aromatic plants [24].

Mechanical harvesting may act as a form of abiotic stress, and stressed plants have been reported to enhance secondary metabolite production as part of their defense response [23]. It has been observed that elicitation through mechanical wounding can significantly alter the expression of genes involved in the terpene biosynthetic pathway, often favoring the accumulation of defense-related compounds [25]. Furthermore, mechanical damage often results in the immediate release of stored volatiles and the subsequent induction of "herbivore-induced" volatile blends, even in the absence of biotic agents, due to the activation of the octadecanoid pathway [26]. The altered relative abundance of thujone and sesquiterpenes in mechanically harvested samples may be associated with stress-related modulation of terpene biosynthetic pathways and volatile emission dynamics [27].

Overall, the results indicate that the harvesting method is a determinant factor not only for yield parameters but also for the chemical composition, biological activity potential, and safety profile of the essential oil. If quality-oriented production is targeted for *Salvia fruticosa*, manual harvesting appears to be more advantageous for obtaining a therapeutic profile rich in oxygenated monoterpenes.

Table 2. Essential oil composition of manually harvested *Salvia fruticosa.*

RT	RI	Compound	Amount%
8.700	972	α-pinene	2.77
10.483	1027	Camphene	2.57
12.411	1075	β-pinene	4.03
14.939	1131	Myrcene	2.13
16.834	1170	Limonene	1.64
17.746	**1188**	**Eucalyptol**	**43.07**
18.815	1206	γ-terpinene	0.57
19.862	1218	o-cymene	0.29
20.431	1225	α-terpinolene	0.48
26.208	1294	Thujone	2.83
26.934	1303	4(10)-Thujen-3-ol	3.70
27.695	1429	trans-β-Terpineol	0.42
29.861	**1490**	**Camphor**	**20.12**
30.329	1504	Linalool	0.55
30.614	1514	Linalyl acetate	0.88
31.656	1547	Bornyl acetate	1.68
32.247	1565	Caryophyllene	2.54
32.299	1567	Terpinen-4-ol	0.54
34.425	1634	Humulene	1.16
35.124	1656	(+)-4-Carene	1.25
35.368	1664	Endo-Borneol	0.99
36.657	1704	Geranyl acetate	0.14
39.212	1785	Geraniol	0.11
43.266	1914	Caryophyllene oxide	0.4
45.613	1987	Viridiflorol	0.85
47.128	2036	Thymol	0.03
47.341	1501	Eugenol	0.02
TOTAL			**95.76**

Table 3. Essential oil composition of machine-harvested *Salvia fruticosa.*

RT	RI	Compound	Amount%
8.680	972	α-pinene	2.50
8.764	976	α-thujene	0.45
10.461	1026	Camphene	2.50
12.354	1073	β-pinene	2.69
14.896	1078	β-myrcene	1.35

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15.678	1146	α-terpinolene	0.43
16.693	1166	D-Limonene	2.20
17.548	**1184**	**Eucalyptol**	**21.77**
18.778	1205	γ-terpinene	0.85
19.876	1218	p-cymene	1.75
26.422	1296	Thujone	19.94
26.966	1391	cis-sabinol	3.94
29.82	**1489**	**Camphor**	**16.12**
30.308	1504	Linalool	0.33
30.614	1513	Linalyl acetate	0.88
31.629	1545	Bornyl acetate	1.3
32.27	1566	Caryophyllene	5.22
32.492	1573	Aromadendrene	0.12
34.436	1634	Humulene	1.36
35.124	1656	(+)-4-Carene	0.29
35.358	1663	Endo-Borneol	0.96
36.648	1704	Geranyl acetate	0.05
39.206	1785	Geraniol	0.06
43.299	1914	Caryophyllene oxide	1.5
45.699	1990	Viridiflorol	5.84
47.128	2035	Thymol	0.13
47.344	2042	Eugenol	0.04
		TOTAL	**94.57**

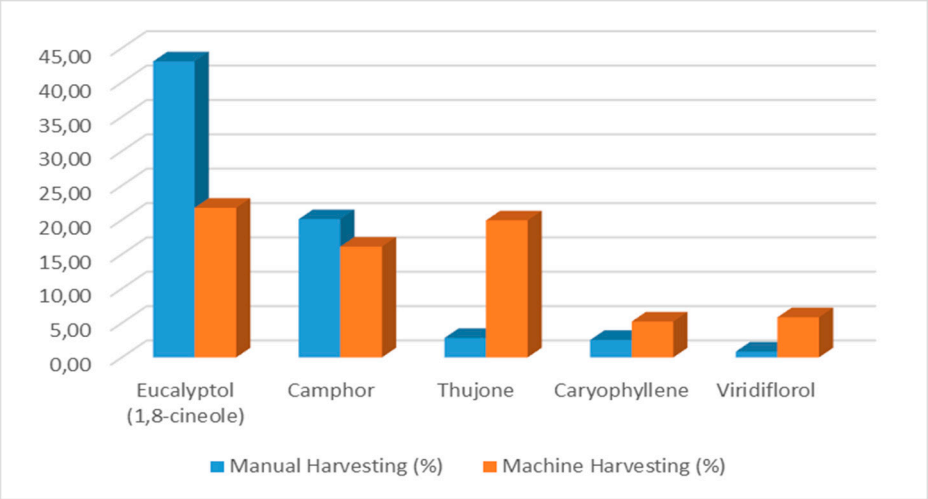

Figure 1. Major components of Anatolian sage oil to hand and machine harvesting.

2.4. Macro and Micro Elements (ppm)

In this study, the effects of machine and manual harvesting methods on the macro and micro element composition of *Salvia fruticosa* (syn. *S. triloba*) were comprehensively evaluated. The macro and micro element contents obtained from manual and machine harvesting are given in Table 4 and Table 5, respectively. The findings indicate that the harvesting method influences not only element concentrations but also the general consistency of the measurements. regarding macro elements, calcium (Ca) and sulfur (S) contents were found to be significantly higher in manually harvested samples. Given the fundamental role of calcium in cell wall structure and membrane stability, it can be postulated that manual harvesting better preserves tissue integrity, while selective leaf picking ensures the inclusion of mineral-rich fractions. Calcium accumulates largely in the cell wall in the form of calcium pectate and remains stable in the tissue due to its lack of phloem mobility. Conversely, the physical impact, friction, and tissue bruising associated with mechanical harvesting may compromise cell wall integrity, leading to the loss or proportional dilution of certain minerals.

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Furthermore, the inclusion of stems and more fibrous tissues in the mechanical harvest likely reduces the overall mineral density.

The higher levels of potassium (K) and phosphorus (P) observed in manual harvesting can be attributed to the selection of metabolically active, leaf-dominant tissues. These elements play critical roles in energy metabolism, osmotic balance, and cellular regulation processes. In contrast, the higher magnesium (Mg) content found in machine harvesting may be explained by the incorporation of stems and older tissues into the mixture; although Mg is the central atom of the chlorophyll molecule, it can also be present in significant amounts in older tissues.

Regarding microelements, zinc (Zn), copper (Cu), and boron (B) contents were determined to be notably higher in manual harvesting. Zn and Cu serve as cofactors in antioxidant enzyme systems and are closely linked to oxidative stress mechanisms. The superior preservation of cellular structure and tissue integrity in manual harvesting may have limited the loss of these elements. The lack of significant differences in iron (Fe) and manganese (Mn) contents between the two methods can be explained by their presence in more stable fractions within the tissue and their lower mobility.

From a human health perspective, the higher Ca content in manually harvested samples may offer potential contributions to bone mineralization, muscle contraction, and nerve transmission. Additionally, the elevated levels of Zn and Cu are significant for immune system functions, antioxidant defense mechanisms, and cellular repair processes. This suggests that manually harvested *Salvia fruticosa* may possess higher nutraceutical and pharmaceutical value. Overall, the findings reveal that the harvesting method is a determinant factor not only for agronomic yield but also for the chemical quality and functional properties of the plant.

The findings of this study demonstrate that the harvesting method significantly influences the mineral profile of *Salvia fruticosa*. The significantly higher concentrations of calcium (Ca) and sulfur (S) in manually harvested samples align with the physiological role of these elements in plant tissues. Calcium, primarily localized in the cell wall as calcium pectate, provides structural rigidity and membrane stability [28]. The higher Ca levels in manual harvesting can be attributed to the selective collection of leaf-dominant tissues, which are known to be the primary sinks for non-mobile elements like Ca, as opposed to the more lignified and mineral-poor stem fractions often included in mechanical harvesting [29].

The elevated levels of potassium (K) and phosphorus (P) in manually harvested samples further support the "leaf-dominance" hypothesis. Since K and P are highly mobile in the phloem and concentrated in metabolically active tissues, manual selection of younger, more active leaves naturally results in higher concentrations of these elements [30]. Conversely, the higher magnesium (Mg) content observed in machine harvesting may be explained by the inclusion of older leaves and stems; while Mg is mobile, it remains relatively stable in older tissues even as other elements are translocated to newer growth [31].

Regarding microelements, the notably higher zinc (Zn), copper (Cu), and boron (B) contents in manual harvesting are significant from a nutraceutical perspective. Zn and Cu are essential cofactors for antioxidant enzymes such as superoxide dismutase (SOD), which protects the plant against oxidative stress [32]. The preservation of these elements in manual harvesting suggests that the lower physical impact prevents the leaching or degradation often associated with the tissue bruising and cellular rupture occurring during mechanical operations [8].

Furthermore, the absence of significant differences in iron (Fe) and manganese (Mn) concentrations suggests that these micronutrients are predominantly associated with structurally stable cellular fractions and enzyme complexes, rendering them less sensitive to mechanical harvesting variations [28–32]. Ultimately, the superior mineral profile of manually harvested *Salvia fruticosa* emphasizes its higher potential for use in pharmaceutical and functional food applications, where mineral density and tissue integrity are paramount.

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Table 4. Macro elements of manually and machine-harvested *Salvia fruticosa.*

Harvesting Methods	Macro Elements				
	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	S (ppm)
Manual Harvesting	1683.13±2.45	11350.17±5.73	32564.92±57.72	4960.92±4.26	2838.67±11.80
Machine Harvesting	1560.66±1.33	10640.23±28.93	12573.18±32.27	5894.43±11.11	1845.32±2.27

Table 5. Micro elements of manually and machine-harvested *Salvia fruticosa.*

Harvesting Methods	Micro Elements				
	Fe (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	B (ppm)
Manual Harvesting	840.28±2.06	15.12±0.54	6.69±0.11	30.98±0.10	40.58±0.09
Machine Harvesting	805.52±3.02	9.53±0.09	4.72±0.09	31.71±0.36	33.20±0.63

2.5. Antioxidant Activity

The results of this study indicate that the antioxidant activity of *Salvia fruticosa* remains relatively stable regardless of the harvesting method employed. The lack of significant differences between manual (0.093 mg TE mL^{-1}) and machine harvesting (0.096 mg TE mL^{-1}) suggests that the primary compounds contributing to the radical scavenging capacity are robust and not easily degraded by the physical impacts of mechanization.

The resilience of the antioxidant potential can be attributed to the stability of the total phenolic pool, particularly rosmarinic acid and other flavonoids, which are the main drivers of antioxidant activity in Salvia species [33,34]. Similar findings have been reported in stressed plant tissues, where phenolic antioxidants remained relatively stable despite stress-induced changes in volatile emissions [32].

Furthermore, while mechanical stress can trigger the production of reactive oxygen species (ROS), it simultaneously induces the plant's enzymatic and non-enzymatic antioxidant defense systems as a compensatory mechanism [36]. It has been documented that moderate mechanical wounding can even promote the accumulation of certain phenolic compounds through the activation of the phenylpropanoid pathway, thereby maintaining or slightly enhancing the overall antioxidant capacity [32].

The observation that machine harvesting does not detrimentally affect the antioxidant profile is a crucial finding for the industrial processing of S. fruticosa. It confirms that mechanization can be adopted to enhance labor efficiency without compromising the nutraceutical quality of the final product. These results align with the broader consensus that while volatile fractions are sensitive to harvesting techniques, the more stable phenolic fractions—responsible for the bulk of antioxidant activity—are less susceptible to operational variations [37,38]. The strong antioxidant capacity observed in the present study may also be associated with the presence of phenolic compounds such as rosmarinic acid, which has been identified as a major antioxidant constituent in several medicinal Lamiaceae species [39].

Table 6. Antioxidant Activity of manually and machine-harvested *Salvia fruticosa.*

Harvesting Methods	Antioxidant Activity (mg TE mL^{-1})
Manual Harvesting	0,093±0,001
Machine Harvesting	0,096±0,001

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2.6. Some Operational Characteristics of Machine and Manual Harvesting

During the studies, the machine forward speed was determined as 3 km h^{-1}, and the average machine work efficiency at this speed was calculated as 0.315 ha h^{-1}. The calculated work efficiency may vary depending on the idle time.

It was determined that the hourly work efficiency of a worker ranged between 0.0114 – 0.0138 ha h^{-1}. The worker efficiency varies depending on plant density and the transport distance of the harvested plants.

Machine work efficiency was determined to be approximately 25 times that of human work efficiency. In other words, the area harvested by a machine can be harvested by eight workers in the same amount of time. While 1 ha of land can be harvested in approximately 3,18 hours with the machine, it can be harvested in 80 hours with a worker. Considering the difficulty of accessing labor and the high cost of labor, especially in the harvesting of large areas, the necessity of harvesting with a machine is understood.

Substantial increases in effective field capacity are commonly observed in mechanized harvesting systems due to reduced labor dependency and higher operational continuity. In contrast, manual harvesting performance is inherently variable and strongly affected by plant density, field layout, and handling logistics. From a machinery management perspective, effective field capacity is primarily influenced by forward speed, working width, and field efficiency parameters [40].

Given the increasing constraints in accessing seasonal agricultural labor and the rising costs of manual work, the transition toward mechanized systems is widely recognized as a key factor for economic sustainability in crop production systems [41]. These findings indicate that while manual harvesting may remain suitable for small-scale, high-value production, mechanized harvesting offers clear advantages in meeting large-scale market demand and maintaining competitive production efficiency.

3. Materials and Methods

3.1. Trial Area and Plant Material

The field experiments were carried out during the 2024 growing season at a dedicated research site in the vicinity of Göztepe, Karaman, Türkiye (37.18° N, 33.22° E; ~1050 m a.s.l.). The region is characterized by a semi-arid continental climate with high solar irradiance, low relative humidity, and pronounced diurnal temperature fluctuations, conditions that are highly conducive to secondary metabolite accumulation in aromatic species. The soil at the experimental site exhibited a clay-loam texture with low organic matter content and a slightly alkaline reaction (pH ~7.8). S. fruticosa Mill. (syn. S. Triloba L.) was harvested at the full flowering stage on 15 July 2024. Images of Anatolian sage are given in Figure 1.

Figure 1. Pictures of Anatolian sage (*Salvia fruticosa*).

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3.2. Harvesting Methods

The study focused on a perennial Lamiaceae species, Anatolian sage (*Salvia triloba* L.; syn. *Salvia fruticosa* Mill "The experimental site was established by a commercial grower for essential oil production. The plantation, established in 2022, covers a total area of 12 da and includes *Salvia fruticosa* Mill. The S. fruticosa plants were established with an inter-row spacing of 1500 mm and an intra-row spacing of 600 mm.

To ensure phytochemical consistency across treatments, *Salvia fruticosa* plants were harvested at the full flowering stage corresponding to phenological stage 65 on the BBCH scale. This harvest timing was selected to capture the period when essential oils and bioactive compounds reach their highest concentrations within the glandular trichomes [11].

Machine harvesting

Machine harvesting was performed using a tractor-mounted medicinal and aromatic plant harvesting machine powered by a hydraulic motor system. The machine had an adjustable cutting width ranging between 0.50 and 1.50 m. The power transmission was provided through a PTO system operating at 540 rpm, and harvesting was carried out at a forward speed of 3 km h^{-1}. Cutting height and working depth were kept constant across all plots. The harvested biomass from each plot was collected and weighed separately.

Manual harvesting

Manual harvesting was performed using a traditional sickle. To ensure comparability between the methods, plants were manually cut at the same height as the mechanical harvester. Harvested plant material was immediately weighed to determine fresh biomass.

3.3. Determination of Some Pre- and Post-Harvest Physical Characteristics

Plant height was measured at the full flowering stage during harvest by recording the distance from the soil surface to the highest vegetative point on randomly selected plants within each plot, excluding border rows. Plant diameter was determined based on the widest canopy width pre-harvest and repeated on the same plants post-harvest to evaluate the effect of the harvesting mechanism on plant morphology. Cutting height was determined by measuring the distance between the soil surface and the cutting point after harvest.

To estimate harvest losses, the number of shattered plants and uncut plants, along with the total tillering count, were recorded for each plot. The harvest loss percentage was calculated using the following formula [12]:

Harvest Loss (%) = [(Number of Uncut Plants + Number of Shattered Plants) / Total Tillering Count] × 100

Fresh weight per plant was determined by weighing harvested plants, and samples were dried at 65 °C until constant weight to determine dry weight per plant. Herbage yield was calculated by weighing the total fresh biomass obtained from each plot and converting the values to an area basis (kg ha^{-1}), while dry herbage yield was determined using dry matter content. All morphological measurements were conducted on a minimum of five plants per plot according to standard procedures [13,14].

3.4. Determination of Essential Oil Content and Yield

The essential oil content was isolated from the dried aerial parts of the plants via hydrodistillation using a Clevenger-type apparatus. The distillation process was conducted for a duration of 3 hours, strictly following the protocols described in the European Pharmacopoeia [15]. The obtained essential oil volume was read directly from the graduated tube, and the content was expressed as volume per dry weight (v/w; mL 100 g^{-1}). GC-MS instrument was used to determine the essential oil components. The essential oils were stored at -200C until analyzed. To determine the essential oil yield per hectare (L ha^{-1}), the essential oil content ratio was extrapolated by multiplying it with the total dry herbage yield values obtained from the respective plots.

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3.5. Essential Oil Composition

GC-MS analysis was performed on a Agilent 6890N Network GC system combined with Agilent 5975 C VL MSD Network Mass Selective Detector. The GC conditions were; column, DB Waxe tr; 60.0m x 0.25mm x 0.25µm; oven temperature programme: The column held initially at 60 0C for 10 min after injection, then increased to 22 0C with 4 0C min-1 heating ramp for 10 min and increased to 240 0C with 10 0C min-1 heating ramp without hold; inject or temperature 250 0C; carrier gas; He; inlet pressure, 9.60 psi; linear gas velocity, 7 cm sec-1; initial flow 0.3 ml min-1; split ratio,65.0:1; injected volume 1.0 µl. Computer matching against commercial libraries (Wiley GC–MS Library, Adams Library, MassFinder 3 Library) as well as MS literature data was used for the identification of essential oil components [15].

3.6. Determination of Macro and Micro Elements

The macro and micro elements of *Salvia fruticosa* herb were determined by inductively coupled plasma mass spectrometry (ICP-MS) following the NMKL Method No. 186. Approximately 0.5 g of dried and ground sample was subjected to microwave-assisted acid digestion using concentrated nitric acid (HNO3). The digested solutions were diluted with ultrapure water and analyzed by ICP-MS. Elemental concentrations were calculated based on external calibration curves prepared using certified standard solutions. Results are expressed in mg/kg (ppm) of dry weight. The method provides high sensitivity and accuracy for multi-elemental analysis in food matrices [16].

3.7. Determination of Antioxidant Activity

Preparation of Plant Extracts

The dried plant samples were ground into a fine powder. For the extraction process, 10 g of the powdered plant material was accurately weighed and mixed with 100 mL of ethanol. The mixture was agitated at room temperature to ensure efficient extraction of bioactive compounds. The resulting extract was then filtered through Whatman No. 1 filter paper to remove solid residues. The clear filtrates were stored at 4 °C until the antioxidant analysis was performed [15].

Antioxidant Activity

Antioxidant activity was determined using the DPPH radical scavenging method described by Brand-Williams et al. (1995) [17]. First, a standard Trolox stock solution was prepared in methanol, and a calibration curve was constructed using varying concentrations of this standard. For the assay, 4 mL of a 0.004% (w/v) DPPH (1,1-diphenyl-2-picrylhydrazyl) solution was added to the plant extracts and Trolox standards. The samples were incubated in the dark at room temperature for 30 min, after which the absorbance values were measured spectrophotometrically at 517 nm. The DPPH radical scavenging activity was calculated using the linear equation of the calibration curve and expressed as Trolox equivalents (mg TE mL^{-1}).

3.8. Determination of Some Operational Characteristics of Machine and Manual Harvesting

Machine work efficiency: During harvesting, the operational performance parameters of the machine were determined and calculated according to the following formula [12];

$S_a = 0{,}1.B.V.K$

S_a: Machine field capacity (ha h^{-1})

B: Working width (m)

V: Forward speed of the machine (km h^{-1})

K: Field efficiency coefficient (%)

Labor (worker) field capacity: During manual harvesting, the time required for a single worker to harvest one plant and a defined group of plants within a specified distance was recorded. Harvest duration was determined accordingly, and the harvested area within that time was converted to a unit area basis (ha).

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5. Conclusions

This study clearly demonstrates that harvesting method in *Salvia fruticosa* (*Salvia triloba*) is not merely an agronomic operation, but a critical production factor directly determining phytochemical quality and product standardization. Machine harvesting induced structural disruption of plant tissues, leading to alterations in the relative distribution of volatile constituents and consequent reductions in essential oil yield, certain mineral contents, and the concentration of major components. In addition, higher harvest losses and a decline in biomass yield—primarily associated with cutting height—were observed under machine harvesting conditions. These differences can be attributed to post-harvest volatilization losses, oxidative transformations, and glandular trichome damage resulting from increased mechanical stress. Notably, antioxidant activity was not significantly affected by harvesting method, indicating that the overall biological potential of secondary metabolites was largely preserved despite compositional shifts.

On the other hand, the substantial increase in operational efficiency achieved through machine harvesting represents a major advantage for large-scale production systems. Although manual harvesting may be feasible in small-scale cultivation, machine harvesting appears indispensable for sustainable and economically viable sage production. This consideration becomes particularly critical under the semi-arid continental ecological conditions of Central Anatolia, such as those prevailing in the Karaman region, where environmental constraints and resource limitations necessitate both efficiency and quality preservation in production systems.

Given that relatively limited research has been conducted both in Türkiye and globally on the comparative effects of harvesting methods on quality parameters in medicinal and aromatic plants, the present findings provide valuable contributions to the existing body of knowledge. Studies addressing quality variations according to harvesting systems are of considerable importance for the standardization and sustainable production of medicinal plants. Therefore, further comprehensive investigations are required to deepen our understanding of harvesting-related quality dynamics and to support evidence-based mechanization strategies.

Therefore, the redesign and optimization of mechanization parameters based on scientific evidence offer a realistic pathway to minimizing quality losses observed under machine harvesting and achieving phytochemical profiles comparable to those obtained through manual harvesting. Such an approach will not only enhance production efficiency but also contribute strategically to sustainable cultivation models, quality assurance, standardization, and the international competitiveness of medicinal and aromatic plant production systems operating under semi-arid ecological conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

EO	Essential Oil
GC–MS	Gas Chromatography–Mass Spectrometry

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ICP–MS	Inductively Coupled Plasma–Mass Spectrometry
DPPH	2,2-Diphenyl-1-picrylhydrazyl
TE	Trolox Equivalent
Ha	hectare

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