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Effect of Organic and Mineral Fertilizers on Essential Oil Yield and Composition of *Thymus syriacus* Boiss. Cultivated Under the Mediterranean Conditions

Nadire Pelin BAHADIRLI[1]✉, Mehmet BAHADIRLI[2]
[1]Hatay Mustafa Kemal University, Department of Field Crops, Faculty of Agriculture,31034, Hatay, Türkiye, [2]Ministry of Agriculture and Forestry, 31034, Hatay, Türkiye
[1]https://orcid.org/0000-0001-7321-5377, [2]https://orcid.org/0000-0002-1242-6485
✉: pelinbahadirli@gmail.com

ABSTRACT

Thymus syriacus Boiss. It is an evergreen, perennial sub-shrub that is distributed throughout the Eastern Mediterranean, including Türkiye. The use of organic and mineral fertilizers differs in their contributions to sustainability and soil fertility. While the mineral fertilizers are believed to ensure rapid nutrient availability, organic fertilizers play a vital role in maintaining long-term soil health and supporting sustainable production systems. In the present study, a field experiment on *T. syriacus* Boiss. was conducted to examine the effects of organic and mineral fertilizers on essential oil (EO) content and composition in the Eastern Mediterranean Region of Türkiye. The treatments included control (no fertilizer), manure (25 ton ha^{-1}), vermicompost (10 ton ha^{-1}), and mineral fertilizer (0.4 ton ha^{-1}). Treatments were found to be significantly effective on EO content and components ($p<0.05$). In both years, control had lower EO content (1.12-1.87%); furthermore, vermicompost had the highest EO content (1.30-2.57%). In the 2nd year, fertilizer applications had significantly improved essential oil content compared with the control. Carvacrol and *o*-cymene were found as the main components. Carvacrol content ranged from 62.98% to 84.56%, with the highest observed in second-year vermicompost-applied samples. As a result, vermicompost organic fertilizer can be recommended for the sustainable cultivation of *T. syriacus*, as it improves soil health while maintaining high essential oil yield and carvacrol content similar to or even greater than those achieved with mineral fertilizers.

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Organik ve Mineral Gübrelerin Akdeniz Koşullarında Yetiştirilen *Thymus syriacus* Boiss. Bitkisinin Uçucu Yağ Verimi ve Bileşenleri Üzerine Etkisi

ÖZET

Thymus syriacus Boiss., Türkiye dahil olmak üzere Doğu Akdeniz'de yayılış gösteren, her dem yeşil, çok yıllık yarı çalı formunda bir türdür. Organik ve mineral gübrelerin kullanımı, sürdürülebilir tarımsal üretim açısından önem taşımakta olup, bu iki gübre türü toprak verimliliği ve bitki performansı üzerindeki etkileri bakımından farklılık göstermektedir. Bu çalışmada, organik ve mineral gübre *T. syriacus* 'un uçucu yağ (UY) içeriği ve bileşenleri üzerindeki etkileri Doğu Akdeniz koşullarında araştırılmıştır. Denemede dört farklı uygulama 2 yıl süreyle değerlendirilmiştir: kontrol (gübre uygulanmamış), mineral (0.4 ton ha^{-1}), ahır gübresi (25 ton ha^{-1}), ve vermikompost (10 ton ha^{-1}). Çalışmada uygulamaların UY içeriği ve bileşenleri üzerinde önemli ölçüde etkili olduğu bulunmuştur ($p<0.05$). Her iki yılda da kontrol uygulamasında EO içeriği daha düşük (%1.12–%1.87) bulunurken, solucan gübresi uygulamasında en yüksek EO içeriği (%1.30–%2.57) elde edilmiştir. İkinci yılda gübre uygulamaları kontrol grubuna kıyasla uçucu yağ içeriğini belirgin biçimde artırmıştır. Ana bileşenler karvakrol ve *o*-simen olarak belirlenmiş; karvakrol oranı %62.98 ile %84.56 arasında değişmiştir. En yüksek karvakrol içeriği, ikinci yılda vermikompost uygulanan örneklerde saptanmıştır. Sonuç olarak, vermikompost gübrelemesi *T. syriacus* yetiştiriciliğinde yüksek uçucu yağ ve karvakrol

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elde edilmesi ve sürdürülebilirliğin sağlanması amacıyla tavsiye edilebilir.

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INTRODUCTION

Soil naturally contains essential elements in mineral forms, but prolonged biological and chemical processes convert them into small amounts of available useful forms. Therefore, the use of soil fertilizers is necessary for high-quality and productive crops. Mineral fertilizers have been the main source of soil fertilizers, but environmental pollution, negative effects on soil microorganisms, and their capacity to reduce soil fertility are among the biggest challenges in their use (Chen 2006). This situation has caused growers to turn to organic fertilizers such as different types of manure, vermicompost, and biochar, or their combination with mineral fertilizers. Vermicompost is a physically, nutritionally, and biochemically improved humus-like organic waste that undergoes a decomposition process with the addition of earthworms (e.g., Eisenia fetida, Eudrilus eugeniae, and *Perionyx excavates*) (Lim et al. 2015). This process differs from traditional composting because the mineralization rate of organic matter is accelerated, and a higher degree of humification can be achieved through vermicomposting (Garg and Gupta 2009). Manure is another slow-release fertilizer that has been applied to soils for centuries. Manure affects soil health through soil fertility, water-holding capacity, and other soil properties (Rayne and Aula 2020). Medicinal plants are grown for their secondary metabolites, which are affected by organic and inorganic factors easily. The main purpose of fertilizer use in medicinal plant cultivation is to increase biomass production without decreasing essential oil content and components (Nikou et al. 2019). In the study carried out on the T. syriacus and T. spicata from the flora of Iraq, thymol was the main component of T. syriacus, DPPH radical scavenging activity was higher in *T. syriacus* than in *T. spicata* (Jamil et al. 2010).

The Lamiaceae family has widespread distribution, containing about 236 genera, many of which are commercially important. The genus *Thymus* is an important part of the family, with approximately 215 species, especially *Thymus vulgaris* L., garden thyme (Vouillamoz and Christ 2020). The Flora of Türkiye includes 40 Thymus species, 20 subspecies, and 19 endemic species (Guner et al. 2012). The genus Thymus originated in Anatolia, however most traded *T. vulgaris* does not naturally occur in the flora. *The thymus genus has been used for its essential oil, as a spice, flavor to food products, cosmetics,* and medicinal supplements (Stahl-Biskup and Saez 2002; El-Gabali et al. 2023). Essential oil of thyme has antimicrobial, antioxidant, and anti-inflammatory properties (Nikolic et al. 2014; Al-Shnani et al. 2016; Battah et al. 2022).

T. syriacus is an evergreen herbaceous, perennial, sub-shrub with white to light pink flowers (Kaya 2019). The species is distributed in Syria, Lebanon, Jordan, Iraq, Iran, and in the Türkiye Southeastern part of Anatolia in Türkiye. Although the species is cultivated and used among the people in Syria, this use has not been reported in Türkiye (Al-Mariri et al. 2013). Main components of *T. syriacus* essential oil were reported as thymol (49.04%), carvacrol (15.87%) and *p*-cymene (6.75%) from Gaziantep, Türkiye (Tumen and Baser 1994). Latest reports on *T. syriacus* essential oil composition from Lebanon, Syria, and Türkiye showed that carvacrol, followed by thymol, are the main components (Hafi et al. 2017; Ayanoglu et al. 2018; Alia and Akrama 2020).

Soil fertility depends on the soil's physical, chemical, and biological properties at the desired levels. Organic matter of soil should be above at least 3% for high fertility; however, Türkiye's 90.1% of soils in Türkiye were found to be lower than the required level. For that reason, fertilizer usage is essential for cultivation. There are several works examining the effects of fertilizers on the biomass production and variation in secondary metabolites of *Thymus* species. Baranauskiene et al. (2003), were studying the effect of different levels of nitrogen fertilizers on *T. vulgaris* yield and composition, while Hendawy et al. (2010) investigated organic fertilization on *T. vulgaris*. There are different forms of fertilizer elements, and their effects on plants cannot always be positive. Fertilizer application studies are very crucial, especially for the cultivation of medicinal and aromatic plants. Liquid cattle dung and humus were investigated on *Thymus* × *citriodorus, which* had positive and negative effects depending on the year (Vaiciulyte et al. 2022). However, comparative long-term field studies on the effects of organic fertilizers, particularly vermicompost, on the essential oil yield and composition of *T. syriacus* remain limited.

The objectives of the research were to investigate the effect of different organic and mineral fertilization on *T. syriacus* essential oil content and components. The presented results will contribute to the utilization of fertilizer for the standardization and domestication of the species.

MATERIAL and METHOD

Plant Materials

Thymus syriacus cuttings from Antakya, Hatay, were used as plant material. Five- to ten-cm cuttings were taken from the native population in December 2019. The cuttings were dipped in water, and any rooting hormones were applied. Cuttings were immediately planted in containers that contained peat and perlite (2:1) medium in the greenhouse.

Experimental Design and Growth Conditions

The study was carried out in agricultural fields in Reyhanli, Hatay, within Türkiye's East Mediterranean region (36°18' 02.5" N and 36° 34' 51.5" E) at an altitude of 115 m above sea level, during 2020-2021. The climate is semi-arid with a mean annual precipitation of 431.9 mm and an average temperature of 19.2 °C (Table 1). The table shows that 2020 was a dry season compared to 2021 and the long term. After the spring frosts, the rooted cuttings were planted in the field in April 2020. The experiment design was a randomized block with three replications. Row and intra-row spacing were 70 cm x 45 cm, with 36 plants per plot. Each plot contained six lines. The treatments were controlled (without fertilizer), manure (25 ton ha-1), vermicompost (10 ton ha-1), and mineral fertilizer (0.4 ton ha-1). The treatments were applied manually to the plots, and the soil was mixed with shovels. Weeds were controlled with hand-hoeing tools when necessary, and drip irrigation was used for watering. Disposed of side effects, fifteen plants from the inside rows of each plot were used for the determination of further properties and analyses. Each plot was harvested at the inflorescence stage (80% flowering) in July 2020 and June 2021, with inflorescences cut 10 cm above ground. Dry leaf biomass, dry leaf yield, and essential oil extraction were determined from 500 g samples per plot. Harvested plants were dried at room temperature.

Table 1. Climate parameters of the research field (2020, 2021, and long-year average)
Çizelge 1. Deneme alanına ait iklim parametreleri (2020, 2021 ve uzun yıllar ortalaması)

	Year	1	2	3	4	5	6	7	8	9	10	11	12
AMT	2020	8.9	9.6	14.9	18.1	23.2	25.2	29.6	29.6	29.1	24.5	17.7	13.6
ATR		63.6	31.6	49.4	38.2	13.8	0.4	0.0	0.0	0.0	0.2	33.6	5.0
AMT	2021	12.2	13.6	15.6	19.8	25.2	27.3	31.0	31.0	27.8	23.4	17.6	12.9
ATR		0.0	15.8	30.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	158.4
LYT	1980/2021	8.3	10.2	13.7	17.8	22.7	26.3	29.0	29.5	26.9	21.3	14.4	9.7
LYR		98.2	54.58	51.43	36.38	12.67	3.88	0.28	0.05	12.71	22.68	48.2	95.91

* AMT= Annual Mean Temperature (°C); ATR= Annual Total Rain (mm); LYT; Long Years Temperature (°C); LYR= Long Years Rain (mm)

Soil and Fertilizers Nutrient Analysis

Soil samples were collected from 0-30 cm depth at three randomly selected sites in each block before fertilizer application. The soil nutrient analysis of the experiment field was analyzed at MARGEM, Hatay Mustafa Kemal University, and the results were given in Table 2. The vermicompost used in this study was commercially sourced and produced by Eisenia fetida earthworms through biological decomposition of organic waste. As it was a commercial product, no heat treatment was applied. The farmyard manure was supplied from the Selam Practice and Research Farm of Hatay Mustafa Kemal University, whereas the mineral fertilizer was obtained from a commercial source. Organic fertilizers were applied 45 days (15th January), and mineral fertilizer was applied ten days before planting in the first year. In the second year of the experiment, the same application period was performed between rows and mixed with soil by hand. Organic matter, pH, total nitrogen (N), available phosphate (P2O5), and soluble potash (K2O) properties of fertilizers are given in Table 2 (Bahadirli and Dogan, 2021).

Essential Oil Isolation and GC/MS Analysis

For each plot, 25 grams of leaves with three replicates were subjected to hydrodistillation for 3 hours with a Clevenger-type apparatus. The oil percentage was calculated by the volumetric method (v/w) for each sample.

Essential oils were diluted in cyclohexane for gas chromatography mass spectrometry (GC/MS) analysis (1:400). The essential oil components were determined with the GC/MS method (Ulaşlı et al., 2025). Agilent 7890A-5975C devices equipped with an HP-5MS column (30m × 250 µm film × 0.25 µm) were used. Helium was a carrier gas. The detector transfer line temperature was 280 °C. The programmed method was 60 °C for 3 min, then 4 °C min-1 to 210 °C for 15 min, then 10 °C min-1 to 300 °C for 15 min, for a total run time of 79.5 minutes. The components were identified by mass spectrometry with NIST and WILEY databases. The relative retention indices of all compounds were determined by the co-injection of the sample with a solution containing the homologous series of

C8-C40 n-alkanes. Relative retention indices, calculated from n-alkanes and retention times, were also compared with Literature retention indices.

Table 2. Soil and fertilizer properties from the experiment
Çizelge 2. Denemede kullanılan topraklara ve gübrelere ait özellikler

Analyze	Soil	Vermicompost	Manure	Mineral
Sand (%)	32			
Clay (%)	33			
Silt (%)	35			
Ph (25 °C)	8.18	7.50	7.80	-
EC (µS.cm-1)	230			
Lime (%)	32.05			
Organic matter(%)	2.13	43.0	48.0	-
N (%)	0.11	2.40	1.80	15
P (kg mg-1)	8.96	2.10	0.15	15
K (kg mg-1)	282	2.30	0.67	15
Ca (kg mg-1)	4522			
Mg (kg mg-1)	760			
Na (kg mg-1)	51.17			
Fe (kg mg-1)	3.37			
Mn (kg mg-1)	6.72			
Zn (kg mg-1)	0.55			
Cu (kg mg-1)	2.05			

Statistical Analysis

Means of essential oil yield were analyzed by analysis of variance (ANOVA) using SPSS v22 software, and significant differences among treatments were determined by Duncan's multiple range test at $P<0.05$.

RESULTS and DISCUSSION

In this study, the essential oil content of *Thymus syriacus* was measured over two consecutive years under different fertilizer treatments, including a control group without any fertilization. The analysis of variance (ANOVA) results indicated that the main effects of fertilizer and year, as well as their interaction, were statistically significant, while the block effect was not (Table 3). Fertilizer application significantly affected essential oil levels ($F = 99.150$, $p< 0.001$), highlighting clear differences among treatment groups. The year effect was also highly significant ($F = 2953.071$, $p < 0.001$), indicating a strong environmental or seasonal impact on oil production. Moreover, the significant fertilizer × year interaction ($F = 35.877$, $p< 0.001$) suggests that the effectiveness of each fertilizer varied between the two years. The block effect was not statistically significant ($F = 0.291$, $p = 0.752$), indicating that positional variation within the experimental field was minimal. A low mean square error (0.002) further supports the reliability of the findings.

Table 3. Variance analysis results of *T. syriacus* essential oil data
Çizelge 3. T. syriacus uçucu yağ verilerine ait varyans analiz tablosu

Source	df	Mean Square	F	Significance
Fertilizer	3	0.643	99.150	< 0.001
Year	1	6.386	2953.071	< 0.001
Block	2	0.001	0.291	0.752
Fertilizer × Year	3	0.233	35.877	< 0.001
Error	14	0.002		

Note: The analysis was conducted using a two-way ANOVA with interaction. Significance is based on $p < 0.001$ for main effects and interaction.

Given the interaction between fertilizer and year, treatment means were evaluated separately for each year to better capture performance differences over time. Therefore, the results are presented by year to better reflect this interaction. Fertilizer application positively influenced essential oil content in both years (Table 4). In the first year, oil content ranged from 1.12% to 1.30%, whereas in the second year, it increased substantially to 1.87%-2.57%. Although a natural increase occurred in the control group, fertilization notably accelerated this trend: mineral and vermicompost treatments significantly enhanced essential oil accumulation compared to the control

and manure treatments. In the second year, the lowest oil content (1.87%) was recorded in the control, while the highest (2.57%) was achieved with vermicompost application, highlighting the stimulatory effect of fertilizers on essential oil production.

Table 4. Essential oil variation of *T. syriacus* depending on fertilizer application and years (%)
Çizelge 4. T. syriacus'un gübre uygulamasına ve yıllara bağlı uçucu yağ değişimi (%)

Treatment	2020 (Mean ± SD)	2021 (Mean ± SD)	Average (Mean ± SD)
Control	1.14 ± 0.32^{b}	1.87 ± 0.43^{D}	1.50 ± 0.40$^{d\ y}$
Mineral	1.26 ± 0.51^{a}	2.31 ± 0.37^{B}	1.79 ± 0.57$^{b\ x}$
Vermicompost	1.30 ± 0.30^{a}	2.57 ± 0.45^{A}	1.94 ± 0.70$^{a\ x}$
Manure	1.12 ± 0.17^{b}	2.18 ± 0.73^{c}	1.65 ± 0.58$^{c\ y}$

Note: Values are means ± standard deviation. Within each year, means followed by different letters (lowercase for 2020, uppercase for 2021) are significantly different at $p < 0.05$ (Tukey's HSD). Letters in the Average column indicate differences across overall treatment means.

The chemical composition of the essential oils was determined by GC/MS, and the identified components are presented in Table 5. Across the experimental years and treatments, the number of detected compounds ranged from 18 to 22, accounting for 97.18–99.98% of the total oil composition. Carvacrol and *o*-cymene were the predominant constituents in all samples, followed by minor amounts of γ-terpinene, p-cymene, and thymol. In the control treatment, 19 compounds were identified in 2020, representing 99.98% of the total oil, and 21 compounds in 2021, corresponding to 98.40%. These samples contained relatively low carvacrol levels (62.98–65.88%), whereas *o*-cymene was present at comparatively higher proportions (22.01% and 17.09% in 2020 and 2021, respectively). In the mineral fertilizer treatment, the number of identified compounds was similar, and carvacrol content ranged from 80.39% to 83.14%, while *o*-cymene ranged from 5.05% to 9.53%. The vermicompost treatment exhibited comparable values in both years, with consistent levels of the major constituents. In the manure treatment, 18 and 21 compounds were detected in 2020 and 2021, respectively, accounting for 99.48% and 97.75% of the total oil. Carvacrol increased from 72.72% to 81.89%, whereas *o*-cymene decreased from 14.39% to 4.39% over the two-year period.

Table 5. Effects of different fertilizers on *T. syriacus* essential compounds (%)
Çizelge 5. Gübre uygulamalarının T. syriacus'un uçucu yağ bileşenleri üzerine etkisi (%)

RI	LRI	Compound	Control		Mineral		Vermicompost		Manure	
			2020/2021		2020/2021		2020/2021		2020/2021	
933	933	*α*-thujene	0.94	0.75	1.05	0.87	0.97	1.04	0.83	0.90
939	939	*α*-pinene	0.70	1.17	0.75	0.93	0.75	0.69	0.71	0.71
952	952	camphene	0.21	0.26	0.18	0.19	0.20	0.14	0.23	0.20
978	978	*β*-pinene	0.16	0.17	0.16	0.16	0.15	0.14	0.14	0.16
993	993	*β*-myrcene	0.88	0.35	0.90	0.17	0.86	1.05	0.78	0.88
1007	1007	*l-phellandrene*	0.20	0.10	0.18	0.06	0.13	0.16	0.16	0.14
1013	1015	*Δ*-3-carene	0.00	0.07	0.00	0.00	0.00	0.08	0.00	0.08
1020	1020	*α*-terpinene	0.75	0.52	0.75	0.37	0.68	0.67	0.75	0.64
1030	1030	*o*-cymene	22.01	17.09	5.05	9.53	4.93	4.34	14.39	4.39
1034	1032	*p*-cymene	1.05	1.73	1.06	0.00	0.93	1.03	1.08	1.00
1069	1068	*γ*-terpinene	2.35	0.35	2.28	0.00	2.04	2.33	2.73	1.33
1114	1112	cis-sabinene hydrate	0.19	0.67	0.16	0.49	0.26	0.00	0.16	0.20
1154	1153	camphor	0.11	0.15	0.07	0.07	0.11	0.00	0.12	0.14
1175	1178	Borneol	0.36	0.67	0.27	0.35	0.32	0.17	0.43	0.32
1185	1186	4-terpineol	0.22	0.33	0.18	0.35	0.20	0.14	0.16	0.25
1205	1207	carvone	0.00	0.18	0.00	0.14	0.00	0.00	0.00	0.12
1316	1314	thymol	0.51	4.39	0.51	0.66	0.52	0.51	0.45	0.51
1330	1329	carvacrol	62.98	65.88	83.14	80.39	83.57	84.56	72.72	81.89
1428	1428	caryophyllene	2.54	1.61	2.12	2.08	2.19	1.65	2.58	2.50
1469	1469	*α*-humulene	0.07	0.06	0.06	0.05	0.06	0.08	0.00	0.07
1496	1499	*α*-muurolene	0.00	0.00	0.08	0.00	0.05	0.00	0.00	0.00
1529	1526	*δ*-cadinene	0.00	0.00	0.12	0.00	0.08	0.13	0.00	0.11
1531	1531	*γ*-cadinene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
1593	1595	caryophyllene oxide	0.93	2.22	0.95	1.57	0.83	0.85	1.035	1.22
Total			**99.98**	**98.40**	**97.18**	**98.68**	**99.84**	**99.71**	**99.48**	**97.75**

RI: Retention indices obtained from the same analysis, LRI: Literature retention indices

Fertilizer use is essential in cultivation; however, long-term use of mineral fertilizers can degrade soil (Sivojiene et al. 2021). Organic fertilizers, on the other hand, have an advantage over mineral fertilization in long-term usage (Gautam et al. 2020). In a study examining the effects of mineral, organomineral, composite organic, and organic fertilizers on soil microbial activity, it was found that organic and organomineral fertilizers increased soil microbial activity parameters, whereas mineral fertilizers reduced them (Bahadirli and Dogan, 2021). A 10-year study comparing the effects of organic and mineral fertilizers on soil shows that organic fertilization doubled soil carbon, improved soil structure, and stability (Herencia et al., 2011). Effects of organic (quail, cattle, goat) and chemical fertilizers on *T. vulgaris* qualitative and quantitative parameters showed that fertilization with cattle manure resulted in higher essential oil contents and yields; in addition, thymol content increased with increasing manure dose (da Cunha Honorato et al., 2024). Another study on T. vulgaris examined the effects of vermicompost (10 t/ha), compost (20 t/ha), manure (30 t/ha), and a control treatment on biochemical constituents under water-stress conditions. The study demonstrated that vermicompost and manure mitigated the adverse effects of stress factors (Rahimi et al., 2023).

In the present study, essential oil contents were increased in the second year, even in the control group. The very first publications on the essential oil content of T. syriacus reported a very low rate of 0.74% (Tumen and Baser 1994). Studies reveal that different altitudes could affect the oil ratio. For instance, Jamil et al. (2010), found that when altitude increases (400 m to 900 m), the amount of essential oil content also increases from 2.52% to 3.75% in *T. syriacus* samples from Iraq. Lower essential oil contents were reported from Syria at altitudes of 400-1000 m, ranging from 1.99 to 2.12% (Al-Mariri et al. 2013). In the present study, the highest essential oil content was obtained from vermicompost in the second year, at 2.57%, and the experimental fields were at 115 m above sea level. Furthermore, previous results on native plants (from which the cuttings were obtained) reported essential oil content of 2.25-2.35% in samples from higher altitudes than in the field experiment (Ayanoglu et al. 2018). Therefore, genetic background and altitude could play an important role on essential oil content. In addition, plant age is a critical determinant of essential oil content and composition. Several studies on *Thymus* species highlight the influence of plant age on essential oil yield and composition. A three-year organic cultivation study on two *Thymus vulgaris* chemotypes in Italy reported that plants reached maximum yield at a given age (Najar et al., 2021). Likewise, a three-year field experiment on *Thymus* × *citriodorus* showed increasing biomass and essential oil content with plant age, indicating that perennial species achieve optimal production after establishment (Vaičiulytė and Ložienė, 2025). Aging effects (2-8 years) were investigated in Lippia sidoides; the plants with higher essential oil content were younger. In addition, the rate of the main components thymol and carvacrol changed by age (dos Santos et al., 2015). In *Artemisia annua* plants, the highest artemisinin content is observed from younger plants, while higher essential oil is observed from older plants (Farooqi et al., 2008). Nevertheless, the effect of age appears to be species-dependent; in *Cymbopogon citratus*, age had no significant effect on essential oil content (Rocha et al., 2014). Overall, these results indicate that the second-year increase in essential oil yield reflects the natural growth and maturation of perennial *Thymus* species. *T. leptobotrys* and *T. maroccanus* are two endemic medicinal plants from Morocco, and the application of inorganic fertilizers on cultivated material has had a significant impact on their antioxidant activity and chemical composition (Jamali et al. 2012).

Essential oil compositions from different countries varied in the main compounds and their quantities. In the present study, carvacrol and o-cymene were identified as the main components and were influenced by both fertilizer treatments and year (Figure 1). Carvacrol content remained consistently high across all treatments in both years, with the mineral and vermicompost treatments showing the greatest concentrations. In contrast, o-cymene content was highest in the control treatment, with levels declining from 22.01% in 2020 to 17.09% in 2021. Other treatments showed markedly lower o-cymene levels, typically below 10, except for the manure treatment in 2020, which decreased sharply in 2021. These findings suggest that while carvacrol synthesis is relatively stable and favored by mineral and vermicompost amendments, o-cymene accumulation is more variable and appears sensitive to both treatment type and annual environmental variation. The essential oil composition from Lebanon showed that carvacrol (57.26%) and thymol (16.80%) were the main compounds (Hafi et al. 2017). Corresponding to Lebanon, Syrian ethanolic extracts mainly consisted of carvacrol (33.4-39.5%), ß-caryophyllene (5.3-6.17%), and farnesol (5.8-6.5%) across collecting sites (Al-Mariri et al. 2013). Carvacrol was found at very high levels in samples from the flora of Hatay, Türkiye, ranging from 81.98% to 85.73% during the pre-flowering and full-flowering periods, respectively (Ayanoglu et al., 2018). Battah et al. (2025) reported a carvacrol content of 68.36% in *T. syriacus* from Damascus during the blossoming stage. Other studies have also indicated the existence of thymol chemotypes in *T. syriacus* genotypes from Türkiye and Morocco (Tumen and Baser, 1994; Jamil et al., 2010). Our results reveal a strong negative correlation between carvacrol and its putative biosynthetic precursor, o-cymene. Although this initially suggests a direct precursor-product relationship, recent studies (Krause et al., 2021) indicate that p-cymene, a structural analog of *o*-cymene, is not a true intermediate but a shunt product formed

from an unstable dienol. Consequently, the observed decline in o-cymene concurrent with carvacrol accumulation likely reflects a fertilizer-induced enhancement of metabolic flux efficiency. Specifically, fertilizer treatments may upregulate the coordinated activity of CYP71D and SDR1 enzymes, channeling the unstable intermediate toward carvacrol production while minimizing its non-productive diversion to *o*-cymene.

While water stress is known to influence essential oil yield and variation in active compounds (Karalija et al., 2022), the observed differences in active compounds in this study were primarily attributed to plant age and fertilizer applications. Although the lower average rainfall in 2020 compared to 2021 could have potentially affected active compound levels, the controlled irrigation conditions of the experimental site are considered to have minimized this effect.

Carvacrol and thymol are the main components of *Origanum*, *Thymbra*, *Thymus,* and *Satureja* genera essential oils. Carvacrol is responsible for many biological properties of these genera, including antimicrobial, antitumor, antimutagenic, antigenotoxic, analgesic, antispasmodic, and anti-inflammatory (Baser 2008). *Thymus* species mainly contain thymol; however, studies including the present study reveal that *T. syriacus* has chemotypes of thymol and carvacrol as main components. Carvacrol, a type of T. s, could have economic value for cultivation. The response of plants to fertilizers varies considerably. Different levels of nitrogen in T. vulgaris cultivation were studied, and no effects on essential oil content were observed (Baranauskiene et al. 2003). This was similar to our results for the control and manure treatments in the first year. Additionally, combined fertilizers have been found to increase the essential oil quality and quantity of *T. daenensis* (Bistgani et al. 2018).

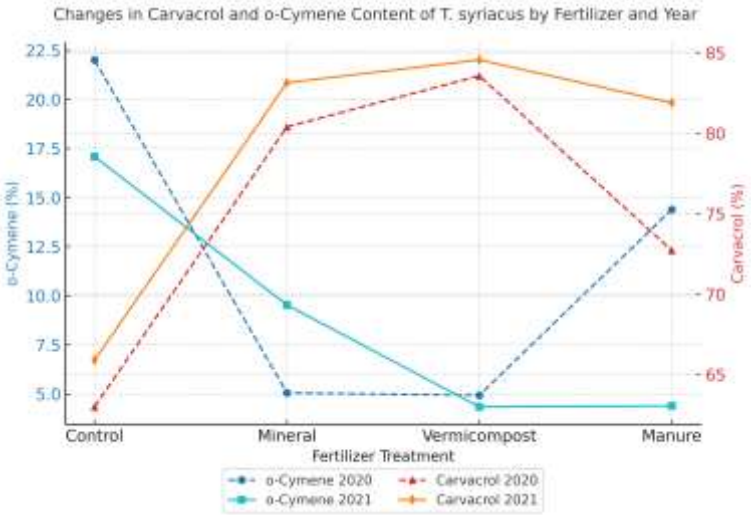


Figure 1. Change in carvacrol and o-cymene content according to years (2020/2021) and applications (%)
Şekil 1. Karvakrol ve o-simen içeriğinin yıllara (2020/2021) ve uygulamalara göre değişimi (%)

CONCLUSION

The present study examined the effects of mineral and two types of organic fertilizer (manure and vermicompost) on the essential oil content and quality of Thymus syriacus. Vermicompost and mineral fertilizers had generally similar effects on the investigated properties. Therefore, vermicompost could be preferable for both soil microorganisms and essential oil properties. Further studies should continue to determine the effects of these fertilizers on soil microorganisms.

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Authors' Contributions

NPB: Conceptualization, Project administration, Investigation, Software. MB: Funding acquisition, Resources, Investigation. NPB, MB; Writing original draft. All authors read and approved the final manuscript.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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