Essential Oil Composition of Achillea arabica Kotschy and Achillea teretifolia Willd from Three Different Microenvironments in Malatya, Türkiye

Turgay KOLAÇ
turgay.kolac@inonu.edu.tr
Inonu University
Melike VURMAZ
Inonu University
Aziz PAŞAHAN
Inonu University
Ali Adnan HAYALOĞLU
Inonu University
Abdussamat GÜZEL
Inonu University

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Abstract

This study characterized the essential oil profiles of two *Achillea* species collected from Malatya Province, Türkiye, using hydrodistillation and analysis in two different laboratories with gas chromatography-mass spectrometry (GC-MS). Samples were collected from three distinct locations for each species, representing local microenvironments. In Laboratory-1 (non-polar column), the major compounds for *A. arabica* Kotschy were camphor (11.97%), eucalyptol (6.77%), borneol (6.17%), and trans-2,7-dimethyl-4,6-octadien-2-ol (5.53%), while for *A. teretifolia* Willd. were found to be eucalyptol (10.97%), piperitone (9.43%), camphor (6.13%), *β*-eudesmol (5.37%), and 4-terpineol (5.27%). In Laboratory 2 (polar column), major compounds for *A. arabica* were bisabolol oxide A (11.97%), palmitic acid (11.43%), *α*-bisabolone oxide A (6.2%), eucalyptol (5.73%), and camphor (5.4%) while for *A. teretifolia* Willd., eucalyptol (14.03%), camphor (12.07%), and piperitone (10.43%) were found. The findings demonstrated statistically significant differences ($p < 0.05$) between species, attributed to genetic and ecological factors rather than analytical errors, as confirmed by replicates showing consistent patterns despite inherent chromatographic variability. Z-score, heat map, PCA and PCA biplot analyses revealed significant chemotypic variations within species across narrow areas. These results highlight the role of geographical origin in chemotaxonomic differentiation and ecological adaptation of *Achillea* species, with implications for method standardization in essential oil studies.

1. INTRODUCTION

The *Achillea* sp. (Asteraceae) is represented by approximately 140 species worldwide, particularly in Europe, Asia, and North Africa. In the flora of Türkiye, it is represented by approximately 60 taxa, a significant portion of which are endemic. Sixteen species have been reported in the flora of Malatya, eight of which are endemic. *Achillea arabica* Kotschy and *Achillea teretifolia* Willd. are among the most common and widely utilized species in the region. Due to their aromatic structure and scent, *Achillea* sp. have long been used in folk medicine for digestive disorders, wound healing, fever reduction, and inflammation relief. Recent pharmacological studies have revealed the antimicrobial, antioxidant, anti-inflammatory, and anticancer potential of these species (Giorgi et al., 2012; Huber-Morath, 1975; Istamkulova et al. 2024; Karakuş, 2016; Özek et al., 2018; Saeidinia, Yassa, et al., 2005; Sezik et al., 1997).

The most important secondary metabolite groups responsible for the biological activities of *Achillea* sp. include essential oil compounds, flavonoids, sesquiterpene lactones, and phenolic acids. Essential oil, in particular, is of great interest due to the diversity of their terpenoid structures and variations in their composition based on ecological, genetic, and location differences. Previous studies have reported *α*-pinene, eucalyptol, caryophyllene derivatives, borneol, and various monoterpene/sesquiterpene derivatives among the major compounds of *Achillea* sp. essential oils (Falconieri et al., 2011; Istamkulova et al. 2024; Kindlovits et al., 2018). In addition, it has been reported that in some species, the fatty acid fraction is also present in significant proportions in the volatile fractions (Özek et al., 2018).

Despite existing studies in the literature, there are limited studies that directly compare samples of *A. arabica* and *A. teretifolia* collected from the same geographical region and examine intraspecific chemical diversity based on narrow location differences. The primary objective of this study is to characterize the essential oil profiles of *A. arabica* and *A. teretifolia*, commonly found in the Malatya flora, using hydrodistillation followed by GC-MS analysis in two laboratories with different conditions. A secondary aim of this study is to compare the effects of extraction and analytical conditions on volatile profiles, thereby assessing methodological impacts and enabling objective multivariate comparisons. This includes identifying both major and minor constituents and comparing the results with previously reported literature data.

The analyses were conducted on samples collected from the same geographical region but analyzed under different laboratory conditions, revealing potential chemotypic differences and environmental influences. Although Malatya represents a relatively narrow geographical area, it lies at the intersection of different climatic zones. As such, microclimatic variations-including differences in soil composition, altitude, rainfall, and sunlight exposure- can lead to significant chemotypic diversity even within small regions. In line with the aim of assessing intra-specific variation, plant materials were collected from three separate microenvironments for each species. Selecting plant materials from three distinct locations allows for the assessment of intra-specific variation. Moreover, conducting analyses on different instruments under varying chromatographic conditions provides additional confidence that observed differences reflect true chemical variability rather than analytical artifacts.

Table 1
Studies on volatiles and essential in *Achillea* sp. in the literature.

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. abrotanoides Vis.	Eucalyptol (18.5%), camphor (14.2%), camphene (10.9%), *β*-thujone (10.2%), bornyl acetate (9.4%)	OV-1 FSOT capillary column (25m x 0.22mm, film thickness 0–5 µm, retention gap 3 m)	-	(Bicchi et al., 1988)
A. ageratum L.	Artemisyl acetate (70.1%), yomogi alcohol (12.4%), artemisia alcohol (7.1%), santolina alcohol (6.1%)	Agilent DB5ms capillary column (30.0m x 0.25 mm ID, 0.25 µm film thickness; model No. 122–5532)	Wild-Leaves	(El Bouzidi et al., 2012)
	Artemisyl acetate (62.3%), santolina alcohol (11.8%), artemisia alcohol (6.4%), yomogi alcohol (4.9%)		Wild-Flowers	
	Artemisyl acetate (78.8%), yomogi alcohol (6.3%), santolina alcohol (4.9%), artemisia alcohol (3.4%)		Cultivated-Leaves	
	Artemisyl acetate (67.4%), santolina alcohol (7.4%), artemisia alcohol (4.4%), yomogi alcohol (6.6%)		Cultivated- Flowers	
A. ageratum L.	Eucalyptol (41.0%), yomogi alcohol (22.3%), santolina alcohol (10%), artemisyl acetate (7.6%), artemisia alcohol (4.1%)	FSC columns (60m x 0.22 mm, film thickness 0.25 µm), Rtx-1 and Rtx-Wax		(Museli et al., 2007)
A. ageratum L.	Artemisyl acetate (70.1%), yomogi alcohol (12.4%), artemisia alcohol (7.1%), santolina alcohol (6.1%)	Agilent DB5ms capillary column (30.0m x 0.25 mm ID x 0.25µm film thickness; model No. 122–5532)		(Kasrati et al., 2015)
A. aleppica DC.	9-Octadecenamide, *(Z)*- (41.7%), hexadecanamide (36.5%), tetradecanamide (10.0%), dodecanoic acid, 3-hydroxy- (3.3%),	BP-5-MS (30 m × 0.25 mm × 0.25 µm)	Ethanolic extract	(Saleh, 2023)
	9-Octadecenamide, *(Z)*- (61.1%), hexadecanamide (20.2%), nonadecanamide (5.6%),		Acetonic extract	
A. aleppica DC.	Camphor (34.0%), eucalyptol (29.0%), camphene (4.0%), isoborneol (3.5%), *p*-cymene (3.1%),	HP-88 capillary column (100 m × 250 µm × 0.20 µm film thickness)	Elazığ/ Hazar-Turkish	(Toncer et al., 2010)
	Camphor (33.0%), eucalyptol (26.1%), thujone (4.1%), isoascaridol (9.4%), *α*-pinene (3.9%),		Elazığ/ Keban-Turkish	
A. arabica	9-Octadecenamide, *(Z)*- (41.3%), hexadecanamide (30.8%), dodecanamide (8.9%), 4-hydroxy-ß-thujone- (5.9%),	BP-5-MS (30 m × 0.25 mm × 0.25 µm)	Ethanolic extract	(Saleh, 2023)
	9-Octadecenamide, *(Z)*- (54.0%), hexadecanamide (14.4%), 13-docosenamide, *(Z)* (7.8%),		Acetonic extract	
A. arabica	*p*-Cymene (14.6%), piperitone (13.1%), camphor (12.8%), eucalyptol (12.0%), borneol (6.5%)	DB-5 FSC column (30m × 0.25 mm id., film thickness 0.25 µm)	Temperate climate.	(Mottaghi et al., 2016)
A. arabica	*m*-Cymene (19.5%), ascaridole (24.2%), terpinolene (11.5%), (-)-terpinen-4-ol (2.9%), 2-*p*-menthen-1-ol (1.5%),	Not specified	-	(Istamkulova et al., 2024)

FSC: Fused silica capillary

SFE: Supercritical extraction

SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. arabica	Eucalyptol (42.3%), *trans*-chrysanthenone (12.7%), *α*-pinene (8.3%), *p*-cymene (5.4%), camphene (5.1%)	HP88 column (60m x 0.25 mm i.d., film thickness 0.25 μm)	-	(CAKICI & KOCAK, 2015)
A. aspleniifolia Vent.	*β*-caryophyllene (17.6%), germacrene D (15.6%), chamazulene (13.3%), caryophyllene oxide (7.2%), (E,E)-*P*-farnesen (4.1%)	PTE-5 capillary column (30 m x 0.25 mm, film thickness 0.25 μm)	-	(Simic et al., 2002)
A. biebersteinii	Eucalyptol (15.0%), camphor (14.6%), piperitone (12.5%), isoascaridol (9.4%), *p*-cymene (7.5%),	HP-88 capillary column (100 m × 250 μm × 0.20 μm film thickness)	Bingöl-Turkish	(Toncer et al., 2010)
	Eucalyptol (31.8%), camphor (27.5%), piperitone (12.0%), terpineol (4.0%), menthol (3.0%)		Mardin-Turkish	
	Ascaridole (62.0%), *p*-cymene (15.6%), eucalyptol (5.1%), camphor (3.2%), carvacrol (1.5%),		Siirt-Turkish	
	Eucalyptol (42.2%), camphor (15.9%), *p*-cymene (5.7%), *α*-pinene (4.5%), *β*-pinene (3.8%),		Elazığ-Turkish	
A. biebersteinii	*p*-Cymene (18.6%), eucalyptol (16.5), camphor (11.7%), hexadecanoic acid (11.2%), *β*-eudesmol (10.1%)	Innowax FSC column (60 m × 0.25 mm, 0.25 μm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. biebersteinii	Piperitone (31.1%), camphor (12.5%), eucalyptol (10.9%), *trans*-ment-2-en-1ol (3.3%)	SGE-BPX5 MS capillary column (30 m x 0.25 mm i.d., 0.25 μm)	Turkish	(Bariş et al., 2006)
A. biebersteinii	Eucalyptol (38.1%), camphor (23.6%), borneol (5.9%), *α*-terpineol (5.2%), terpinen-4-ol (3.3%)	SGE-BPX5 MS capillary column (30 m × 0.25 mm i.d., 0.25 μm)	Essential oil	(Kordali et al., 2009)
	Camphor (18.0%), linoleic acid (16.4%), eucalyptol (15.1%), methyl linoleate (10.2%), borneol (5.2%),		n-hexane extract	
A. biebersteinii	Total oils: Piperitone (34.9%), eucalyptol (13.0%), camphor (8.8%), chrysanthenone (8.2%), borneol (4.4%) Fractions: Piperitone (82.9–1.2%), eucalyptol (6.7–43.5%), camphor (0.1–13.6%), chrysanthenone (-%), borneol (13.2–0.5%)	HP-5 MS (30m x 0.25mm, 0.25 μm film thickness)	Isolation fractions	(Sökmen et al., 2004)
A. biebersteinii	Ascaridole (37.0%), piperitone (17.0%), camphor (12.0%), *p*-cymene (8.0%), piperitone oxide (6.3%),	CP Sil5 CB column, (25 m x 0.25 mm film thickness 0.39 μm)	Iranian	(Rustaiyan et al., 1998)
A. biebersteinii	Eucalyptol (38.1%), camphor (23.6%), borneol (5.9%), *α*-terpineol (5.2%), terpinen-4-ol (3.3%)	SGE-BPX5 MS capillary column (30 m × 0.25 mm i.d., film thickness 0.25 μm)	Essential oil	(Kotan et al., 2010)
	Camphor (18.0%), linoleic acid (16.4%), eucalyptol (15.1%), methyl linoleate (10.2%), borneol (5.2%),		n-hexane extract	
A. biebersteinii	*β*-Eudesmol (19.1%), piperitone (9.2%), cyclohexadecanolide (5.5%), camphor (4.2%), borneol (3.3%),	HP 5 MS Column (30 m × 0.25 mm × 0.25 μm)	Turkish	(Akkol et al., 2011)

FSC: Fused silica capillary

SFE: Supercritical extraction

SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. biebersteinii	Eucalyptol (30.6%), piperitone (28.9%), camphor (11.7%), *p*-cymene 2.5%, camphene (1.9%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Ağrı-Turkish	(Polatoğlu et al., 2013)
	Eucalyptol (31.1%), camphor (14.4%), *α*-thujone (12.9%), *p*-cymene (4.6%), *β*-thujone (3.4%), borneol (3.4%)		Sivas-Turkish	
A. biebersteinii	Eucalyptol (38.1%), camphor (23.6%), borneol (5.9%), *α*-terpineol (5.2%), terpinen-4-ol (3.3%),	SGE-BPX5 MS FSC column (30 m x 0.25 mm i.d., film thickness 0.25 µm)	Essential oil	(Çakır et al., 2016)
	Camphor (18.0%), linoleic acid (16.4%), eucalyptol (15.1%), methyl linoleate (10.2%), borneol (5.2%),		n-hexane extract	
A. biserrata M.Bieb.	Camphor (36.8%), eucalyptol (19.4%), camphene (16.4%), artemisia alcohol (14.3%), Spathulenol (3.5%),	HP-5 MS capillary column (30 m × 0.25 mm i.d. 0.25 µm film thickness)	Turkish	(Azaz et al., 2009)
A. biserrata M.Bieb.	Camphor (33.5%), eucalyptol (17.7%), borneol (11.7%), *cis*-bornyl acetate (10.8%), terpinen-4-ol (8.7%),	SGE-BPX5 MS FSC column (30 m x 0.25 mm i.d., film thickness 0.25 µm)	Essential oil	(Çakır et al., 2016)
	Ethyl oleate (13.1%), camphor (6.7%), eucalyptol (6.0%), isophytol (5.0%), ethyl octadecenoate (3.5%),		n-hexane extract	
A. clavennae L.	Camphor (29.5%), myrcene (5.5%), eucalyptol (5.3%), *β*-caryophyllene (5.1%), linalool (4.9%)	HP-20 M column (50 m × 0.2 mm, 0.2 µm film thickness)	Velebit Mountains	(Bezić et al., 2003)
A. clavennae L.	Camphor (46.9%), eucalyptol (43.9%), camphene (3.1%), *β*- caryophyllene oxide (2.3%)	SPB1 (30 m × 0.25 mm i.d., 0.25 µm film thickness) or DB-5 (30 m × 0.2 mm i.d., 0.25 µm film thickness)	Balkans	(Boskovic et al., 2005)
A. coarctata Poir.	Viridiflorol (37.7%), *α*-cadinol (8.9%), cubenol (6.1%), borneol (5.8%), caryophyllene oxide (3.9%),	SGE-BPX5 MS FSC column (30 m x 0.25 mm i.d., film thickness 0.25 µm)	Essential oil	(Çakır et al., 2016)
	Eucalyptol (30.8%), camphor (16.2%), *α*-pinene (6.2%), camphene (4.7%), *γ*-terpinene (3.3%)		n-hexane extract	
A. coarctata Poir.	Eucalyptol (20.1%), camphor (15.6%), viridiflorol (11.8%), *α*-terpineol (4.7%), borneol (4.6%)	HP-ULTRA2 (50 m x 0.20 mm, 0.33 µm film thickness)	Turkish	(Toker et al., 2003)
A. coarctata Poir.	Eucalyptol (34.2%), camphor (9.2%), *cis*-sabinene hydrate (8.4%), caryophyllene oxide (7.6%), borneol (7.2%)	HP88 column (60m x 0.25 mm i.d., film thickness 0.25 µm)	Turkish	(CAKICI & KOCAK, 2015)
A. coarctata Poir.	Viridiflorol (25.9%), camphor (9.8%), caryophyllene oxide (9.6%), 15-hexadecanolide (9.4%), hexadecanoic acid (8.2%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. collina (Becker ex Rchb.f.) Heimerl	Chamazulene (67.7 ± 47.6), E-2-hexenal (62.4 ± 37.3), *β*-pinene (48.9 ± 15.1), eucalyptol (28.5 ± 15.9), *β*-phellandrene (22.6 ± 0.1)	Rtx-Wax column (30 m; 0.25 mm i.d.; 0.25 µm film thickness, Restek, USA)	Control	(Giorgi et al., 2012)
	Chamazulene (159.0 ± 8.2), E-2-hexenal (45.3 ± 17.4), *β*-pinene (163.1 ± 21.6), eucalyptol (19.5 ± 0.1), *β*-phellandrene (47.3 ± 4.2)		Infested samples	

FSC: Fused silica capillary

SFE: Supercritical extraction

SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. collina (Becker ex Rchb.f.) Heimerl	Heptadecen-7-one (28.9–43.0%), alismol (3.1–18.9%), *β*-sesquiphellandrene (0.5–9.8%), *γ*-humulene (1.1–6.8%), *cis*-cadin-4-en-7-ol (0.3–7.4%), *β*-eudesmol (0.2–7.3%);	HP-5MS (30 m × 0.25 mm, film thickness 0.25 μm)	Root essential oil	(Kindlovits et al., 2018)
	Albene (20.8–52.1%), *β*-pinene (8.3–47.1%), hexanal (1.0-8.4%), *α*-pinene (1.4–8.1%), neryl isovalerate (0.4–2.7%);		Root headspace volatiles	
	Heptadecen-7-one (5.3–17.8%), linoleic acid (0.3–12.0%), 2,4,6-decatrienoic acid piperidide (0.2–14.4%), sterols (19.1–34.7%), triterpenes (4.7–14.1%)		Root dichloromethane extracts	
A. conferta DC.	Camphor (22.1%), eucalyptol (10.0%), borneol (6.2%), *α*-terpineol (4.2%), *cis*-jasmone (4.1%),	HP-5 (30 m × 0.25 mm i.d., 0.25 μm film thickness)	Iranian	(Saeidinia, Gohari, et al., 2005)
A. crithmifolia Waldst. & Kit.	Borneol (21.1%), eucalyptol (15.2%), eudesma-7(11)-en-4-ol (6.0%), camphor (5.9%), *α*-terpineol (5.3%),	DB-5 (30 m × 0.25 mm × 0.25 μm, J & W Scientific, Folsom, USA)	-	(Smelcerovic et al., 2010)
A. cucullata Bornm.	Camphor (32.7%), eucalyptol (29.2%), linalool (3.8%), isoborneol (3.5%), piperitone (3.5%)	HP-88 capillary column (100 m × 250 μm × 0.20 μm film thickness)	Malatya-Turkish	(Toncer et al., 2010)
A. distans Waldst. & Kit. ex Willd.	Eucalyptol (16.8%), *β*-thujone (9.8%), sabinene (8.2%), borneol (7.5%), *β*-pinene (6.5%), camphor (5.8%),	Not specified	Stara Planina mountain	(Konakchiev et al., 2011)
A. eriophora DC.	Eucalyptol (34.2%), *α*-pinene (7.6%), *β*-pinene (6.2%), *α*-terpineol (5.1%), linalol (4.7%),	HP 1 column (15 m x 0:2 mm i.d.), and CP Sil 5 CB column (30 m x 0:25 mm i.d.)	-	(Weyerstahl et al., 1997)
A. eriophora DC.	Camphor (19.6%), eucalyptol (19.1%), camphene (9.6%), *α*-pinene (7.4%), borneol (6.7%)	DB-5 FSC column (30m × 0.25 mm id., film thickness 0.25 μm)	Temperate climate.	(Mottaghi et al., 2016)
A. eriophora DC.	L-Borneol (0-45.9%), bornyl acetate (0-22.5%), bornyl ester (0-10.5%), (E)-*α*-ionol (0-28.8%), 6*β*-bicyclo[4.3.0]nonane5*β*-iodomethyl-1*β*-isopropenyl-4*a*,5*α*-dimethyl (0-12.1%), eucalyptol (0–4.0%)	HP- 5MS column (60 m × 0.25 mm i.d., film thickness 0.25 m)	Southeast Iran 13 ecotypes	(Etehadpour & Tavassolian, 2019)
A. eriophora DC.	Eucalyptol (408), *α*-pinene (198), *p*-cymene (130)-(area)	DB-Wax column (60 m × 0.32 mm with a 0.25 μm film thickness -J & W Scientific, Folsom, CA)	Leaves	(Dokhani et al., 2005)
	α-Pinene (255), eucalyptol (253), *p*-cymene (191)-(area)		Flowers	
A. filipendulina Lam.	Santolina alcohol (37.2%), borneol (12.7%), eucalyptol (8.6%), germacrene D (6.2%), camphor (4.1%),	DB-5 FSC column (30m × 0.25 mm id., film thickness 0.25 μm)	Temperate climate	(Mottaghi et al., 2016)
A. filipendulina Lam.	Eucalyptol (4.5–19.9%), *α*-pinene (19.0-28.3%), camphene (10.2–18.9%), acetaldehyde (3.2–17.4%)	DB-Wax column (60 m × 0.32 mm with a 0.25 μm film thickness -J & W Scientific, Folsom, CA)	Comparison of drying methods	(Dokhani et al., 2012)
A. filipendulina Lam.	Eucalyptol (23.0%), *trans*-2,7-dimethyl-4,6-octadien-2-ol (21.9%), borneol (8.1%),	Elite 5-MS capillary column (0.25 mm i.d. x	Turkish	(Hasimi et al., 2015)

FSC: Fused silica capillary

SFE: Supercritical extraction

SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
	cis-*p*-menth-2,8-dienol (7.9%), terpinolene (6.1%),	30 m, film thickness 0.25 µm)		
A. fraasii Sch.Bip.	Eucalyptol (11.9%), camphor (16.3%), borneol (8.6%), 2,7-dimethyl-4*(E)*,6-octadien-2-ol (8.3%), caryophyllene oxide (3.5%)	HP-5 capillary column (30 m × 0.25 mm L, with 0.25 µm film thickness)	Tymfi mountains	(Magiatis et al., 2002)
A. fragrantissima (Forssk.) Sch.Bip.	*trans*-Sabinyl acetate (20.7–24.0%), *trans*-sabinol (14.9–19.2%), artemisia ketone (12.7–16.3%), santolina alcohol (10.1–10.4%), *β*-sesquiphellandrene (4.8–5.5%), *β*-thujone (3.2–5.1%)	HP-5MS and DB-Wax	Leaf and stem.	(Khan et al., 2020)
A. goniocephala Boiss. & Balansa	Camphor (32.6%), eucalyptol (23.2%), *trans*-sabinene hidrate (6.6%), terpinen-4-ol (5.8%), *α*-terpineol (3.1%),	Innowax FSC column (60 m × 0.25 mm L, with 0.25 mm film thickness)	Kahraman Maraş-Turkish	(K Hüsnü Can Baser et al., 2001)
*A. grandiflora (*Synonym *A. ptarmicifolia* (Willd.) Rupr. ex Heimerl)	*β*-Pinene (8.9%), selin-11-en-4a-ol (8.5%), *γ*-eudesmol (6.3%), eucalyptol (5.9%), camphor (4.0%),	Innowax FSC column (60 m × 0.25 mm L, with 0.25 mm film thickness)	Kazakhstan.	(Suleimenov et al., 2001)
A. gypsicola Hub.-Mor.	Camphor (40.2%), eucalyptol (22.0%), borneol (9.5%), piperitone (11.3%),	SGE/BPX5 MS capillary column (30 m × 0.25 mm i.d., 0.25 µm)	Essential oil	(Kordali et al., 2009)
	Camphor (25.8%), piperitone (17.7%), eucalyptol (15.8%), methyl linoleate (7.6%), linoleic acid (6.3%),		n-hexane extract	
A. hamzaoglui Arabacı & Budak	Eucalyptol (24.1%), linalool (12.2%), camphor (6.7%), germacrene D (6.2%), sabinene (4.0%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. ketenoglui H.Duman	Borneol (14.1%), eucalyptol (13.8%), camphor (13.4%), germacrene D (6.0%), naphthalene (41%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Ankara-Turkish	(Kemal Hüsnü Can Baser et al., 2001)
A. ketenoglui H.Duman	Terpinen-4-ol (14.5%), *trans*-sabinene hydrate (10.9%), *cis*-sabinene hydrate (5.9%), borneol (5.6%), camphor (5.5%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Eskişehir-Turkish	(Kemal Hüsnü Can Baser et al., 2001)
A. holosericea Sm.	Eucalyptol (47.4%), camphor (23.5%), borneol (17.1%), isoborneol (2.4%), camphene (2.1%)	SPB1 (30 m × 0.25 mm i.d., 0.25 µm film thickness) or DB-5 (30 m × 0.2 mm i.d., 0.25 µm film thickness)	Balkans	(Boskovic et al., 2005)
A. holosericea Sm.	Camphor (20.9%), borneol (16.3%), farnesyl acetate *cis, trans* (9.6%), nonanal (4.9%), pinocarvone (3.6%)	HP-5 capillary column (30 m × 0.25 mm L, with 0.25 µm film thickness)	Taygetus mountains	(Magiatis et al., 2002)
A. kotschyi Boiss. subsp. *kotschyi*	Eucalyptol (22.5%), caryophyllene oxide (10.1%), *p*-cymene (8.4%), hexadecanoic acid (7.7%), *β*-Eudesmol (4.9%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. ligustica All.	4-Terpineol (19.3%), carvone (8.9%), *γ*-terpinene (7.2%), *β*-phellandrene (6.8%), *β*-pinene (5.8%)	DB-5 capillary column (30 m x 0.25 mm; coating thickness 0.25 µm)	Leaves	(Bader et al., 2007)
	Linalool (20.4%), 4-terpineol (12.0%), carvone (10.0%), *β*-phellandrene (5.4%), cedrol (4.3%)		Flowers	
A. ligustica All.	Santolina alcohol (6.7–21.8%), borneol (3.4–20.8%), sabinol (2.1–15.5%), *trans*-	DB-5MS (30 m × 0.25 mm; film thickness 0.25 µm).	Different localities of Sardinia	(Tuberoso et al., 2005)

FSC: Fused silica capillary

SFE: Supercritical extraction

SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
	sabinyl acetate (0.9–17.6%), *α*-thujone (0.4–25.8%)			
A. lingulata Waldst. & Kit.	τ-Cadinol (22.5%), caryophyllene oxide (16.6%), *α*-bisabolene oxide (12.8%), borneol (8.0%), geraniol (4.22%),	SPB1 (30 m × 0.25 mm i.d., 0.25 µm film thickness) or DB-5 (30 m × 0.2 mm i.d., 0.25 µm film thickness)	Balkans	(Boskovic et al., 2005)
A. lycaonica Boiss. & Heldr.	*trans*-Sabinene hydrate (9.3%), terpinen-4-ol (9.0%), caryophyllene oxide (7.2%), linalool (4.4%), *cis*-sabinene hydrate (4.2%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Karaman-Turkish	(Kemal Hüsnü Can Baser et al., 2001)
A. lycaonica Boiss. & Heldr.	Nonacosane (10.6%), heptacosane (9.2%), pentacosane (6.1%), spathulenol (4.6%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. lycaonica Boiss. & Heldr.	L-Camphor (43.2%); artemisia alcohol (21.2%), camphor (16.5%), eucalyptol (6.0%), camphene (3.1%),	HP-5 MS capillary column (30 m × 0.25 mm i.d. 0.25 µm film thickness)	Sivas-Turkish	(Azaz et al., 2008)
A. magnifica Heimerl ex Hub.-Mor.	Eucalyptol (30.4%), camphor (23.2%), *α*-pinene (5.3%), camphene (4.0%), *p*-cymene (3.7%)	HP-88 capillary column (100 m × 250 µm × 0.20 µm film thickness)	Erzurum-Turkish	(Toncer et al., 2010)
A. millefolium L.	3-Cyclohexen-1-one (21.6%), linalool (14.3%), eucalyptol (12.7%), chrysanthenone (8.6%), *trans*-chrysanthenol (7.8%)	Not specified	Turkish	(Kocak et al., 2010)
A. millefolium L.	Eucalyptol (13.2–17.6%), germacrene D (14.1–43.2%), camphor (3.3–4.7%), *β*-cubebene (3.1–4.9%), humulene epoxide (2.0-4.7%),	DB-1 FSC column (60 m × 0.25, 0.25µm film thickness)	Different pressure, temperature, modifier volume and extraction time	(Barghamadi et al., 2009)
A. millefolium L.	Nerolidol *(E)* (25.8 – 0.6%), eucalyptol (21.6–9.4%), *δ*-cadinol(-) (21.6-0%), caryophyllene oxide (11.3–3.9%), *β*-pinene (11.0-0.9%)	SLB-5ms capillary column (30 mx0.25 µm)	Different Altitude	(Radzhabov et al., 2022)
A. millefolium L.	*β*-Pinene (10.6%-17.7%), eucalyptol (3.0%-15.1%), borneol (0.2%-12.1%), *β*-caryophyllene (8.5%-16.2%),	Not specified	Different Himalayan Habitats	(Agnihotri et al., 2005)
A. millefolium L.	Eucalyptol (6.6%), *δ*-cadinol (6.2%), caryophyllene epoxide (5.6%), thymol (4.0%), *α*-terpineol (3.5%),	SGE-BPX5 MS capillary column (30 m × 0.25 mm i.d., film thickness 0.25 µm)	Essential oil	(Kotan et al., 2010)
	Thymol (4.8%), carvacrol (4.7%), isophytol (3.8%), methyl linoleate (3.0%), *α*-bisabolol oxide A (2.7%),		n-hexane extract	
A. millefolium L.	*β*-Pinene (32.6%), *β*-caryophyllene (16.5%), sabinene (11.5%), chamazulene (5.9%), eucalyptol (4.6%),	SPB1 (30 m × 0.25 mm i.d., 0.25 µm film thickness) or DB-5 (30 m × 0.2 mm i.d., 0.25 µm film thickness)	Balkans	(Boskovic et al., 2005)
A. millefolium L.	2-Carene (26.3%), ascaridole (18.9%), *m*-cymene (12.6%), camphor (2.9%), terpinen-4-ol (2.0%)	Not specified	-	(Istamkulova et al., 2024)
A. millefolium L.	Camphor (28.4%), eucalyptol (11.5%), germacrene-D (11.5%), *cis*-chrysanthenyl acetate (7.6%), pulegone (4.4%)	ULBON HR-1, FSC, (0.25 mm x 50 m, film thickness 0.25 µm)	India	(Shawl et al., 2002)
A. millefolium L.	Eucalyptol (28.8%), camphor (11.0%), borneol (5.9%), *β*-pinene (5.4%),	DB-5 (30 m × 0.25 mm × 0.25 µm, J & W	-	(Smelcerovic et al., 2010)

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SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
	caryophyllene oxide (3.3%)	Scientific, Folsom, USA)		
A. millefolium L.	Carvacrol (20.4%), thymol (15.3%), *α*-pinene (10.1%), *γ*-terpinene (8.0%), borneol (5.0%),	HP-5MS (30 m length × 0.25 mm i.d., film thickness 0.25 mm)	Eastern Region of Iran	(Kazemi, 2015)
A. millefolium L.	Camphor (16.0%), eucalyptol (8.7%), borneol (6.2%), *β*-eudesmol (6.1%), *α*-terpineol (5.9%)	Innowax FSC column (60 m × 0.25 mm L, with 0.25 mm film thickness)	Kazakhstan	(Suleimenov et al., 2001)
A. millefolium L.	*β*-Caryophyllene (10.6–13.7%), sabinene (9.6–30.1%), *β*-cubebene (9.3–21.6%), borneol (6.0-15.7%), eucalyptol (5.3–7.2%)	HP-5MS FSC column (30 m length × 0.25 mm internal diameter × 0.25 mm thick film)	Different light spectra effect	(Alvarenga et al., 2015)
A. millefolium L.	*α*-Pinene (96), eucalyptol (64)-(area)	DB-Wax column (60 m × 0.32 mm with a 0.25 µm film thickness -J & W Scientific, Folsom, CA)	Leaves	(Dokhani et al., 2005)
	Eucalyptol (950), *α*-pinene (1350), *β*-pinene (674), sabinene (400), *β*-terpinene (381)-(area)		Flowers	
A. millefolium L.	Camphor (9.9%), eucalyptol (5.7%), (+)-2-bornanone (5.6%), caryophyllene oxide (5.6%), *α*-terpineol (4.5%)	HP-5MS (60 m × 0.25 mm L, with 0.25 mm film thickness)	-	(Angourani et al., 2023)
A. millefolium L.	*α*-Asarone (33.3%), *α*-pinene (17.2%), *β*-bisabolene (16.6%), *(E)*-methyl isoeugenol (8.8%), sabinene (3.9%)	Not specified	Essential oil from Sadali	(Falconieri et al., 2011)
	β-Bisabolene (27.3%), *α*-asarone (25.6%), *α*-pinene (10.0%), *trans*-*α*-bergamotene (9.1%), 10-epi-*β*-acoradiene (4.4%),		SFE from Sadali	
	β-Thujone (29.0%), *trans*-chrysanthenyl acetate (15.8%), *β*-pinene (11.1%), camphor (9.7%), sabinene (5.0%)		Essential oil from Montemuro	
	β-Thujone (31.4%), *trans*-chrysanthenyl acetate (19.8%), germacrene D (11.0%), *β*-caryophyllene (5.7%), cubebol (4.8%)		SFE from Montemuro	
A. millefolium L.	Terpinolene (20.0%), *m*-cymene (18.4%), ascaridole (17.9%), *cis*-*p*-mentha-2,8-dien-1-ol (4.2%), camphor (2.5%)	Not specified	From Amonkutan	(Istamkulova et al., 2025)
	Eucalyptol (21.0%), terpinolene (15.8%), ascaridole (12.3%), *cis*-*p*-mentha-2,8-dien-1-ol (4.9%), camphor (2.5%)		From Korabulok	
	2-Carene (26.3%), ascaridole (15.4%), *m*-cymene (12.6%), terpinen-4-ol (2.0%), camphor (2.9%),		From Ilonsoy	
	Ascaridole (20.4%), *m*-cymene (18.8%), terpinolene (6.8%), (-)-terpinen-4-ol (3.0%), eucalyptol (1.9%)		From Sazagan	
A. millefolium subsp. *elbursensis* Hub.-Mor.	Chamazulene (48.9%), isoborneol (10.2%), camphor (9.5%), pinocarvone (5.1%), *p*-cymene (4.0%)	DB-5 FSC column (60 m × 0.25 mm × film thickness 0.25 µm; J & W Scientific, Rancho Cordova, CA).	Flowers	(Alinezhad et al., 2011)
A. millefolium L. subsp. *millefolium*	*α*-Bisabolol (11.7%), caryophyllene oxide (7.7%), muurola-4,10(14)-dien-1-ol (6.8%), hexadecanoic acid (4.6%), eucalyptol (4.1%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)

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Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. monocephala Boiss. & Balansa	Camphor (30.5–28.7%), borneol (15.6–9.9%), *(Z)*-*α*-terpineol (7.3–6.4%), eucalyptol (7.3–4.9%), *α*-terpineol (5.9–5.5%)	DB5 (10 m × 0.18 mm i.d., 0.18 μm film thickness) and DB17 (1.6 m × 0.18 mm i.d.,0.18 μm film thickness).	Leaves	(Gogus et al., 2006)
	Camphor (35.2–33.4%), borneol (23.6–13.9%), *α*-campholenal (15.2–13.9%), eucalyptol (12.4–7.9%), terpinen-4-ol (4.9–4.3%)		Flowers	
A. multifida (DC.) Griseb.	*α*-Thujone (60.9%), *β*-thujone (9.1%), sabinene (4.1%), camphor (3.7%)	HP-Innowax FSC column (60 m x 0.25 mm inner diameter, with 0.25 μm film thick-ness)	Turkish	(Başer et al., 2002)
A. nobilis L.	Camphor (17.0%), eucalyptol (15.6%), terpinen-4-ol (10.0%), borneol (7.2%), *α*-eudesmol (7.1%)	Innowax FSC column (60 m × 0.25 mm L, with 0.25 μm film thickness)	Kazakhstan	(Suleimenov et al., 2001)
A. nobilis subsp. *neilreichii* (A.Kern.) Velen.	Fragranyl acetate (31.8%), fragranol (24.1%), *β*-eudesmol (7.7%),	Innowax FSC column (60 m x 0.25 mm, 0.25 μm film thickness)	Turkish	(Demirci et al., 2009)
A. odorata L.	Camphor (22.9–26.3%), eucalyptol (15.7–17.8%), *α*-pinene (11.3–12.5%), myrtenol (4.3–6.3%), *β*-pinene (3.9–5.7%)	FSC columns (50 m x 0.22mm, 0.25 μm film thickness), BP-1 and BP-20	During the full flowering	(Bekhechi et al., 2011)
	α-Thujone (11.2–21.1%), eucalyptol (12.0-19.4%), camphor (12.2–14.2%), *α*-pinene (5.4–7.3%), borneol (3.2–9.7%)		At the end of flowering	
A. oligocephala DC.	Eucalyptol (18.6%), *α*-terpineol (6.8%), linalool (6.0%), borneol (4.9%), a-bisabolol oxide B (4.5%),	HP ultra2 (50 m x 0.20 mm, 0.33 μm film thickness)	Turkish	(Toker et al., 2003)
A. phrygia Boiss. & Balansa	Camphor (35.6%), 2-furaldehyde (16.6%), eucalyptol (10.1%), borneol (3.6%), (-)-menthone (2.7%),	TR-CN 100 capillary column (60 m x 0.25 mm i.d.; film thickness 0.20 μm)	Nevşehir-Turkish	(Akcin et al., 2014)
A. phrygia Boiss. & Balansa	*cis*-Piperitol (11.2&31.2%), *trans*-*p*-menth-2-en-l-ol (11.0&14.7%), *cis*-*p*-menth-2-en-l-ol (7.2&9.9%), eucalyptol (9.1&9.9%)	DB-5 FSC column (30m × 0.3 mm)	2 locality Eskisehir-Turkish	(Baser et al., 2000)
A. salicifolia Besser subsp. *salicifolia*	Camphor (55.3%), eucalyptol (22.8%), 2,5,5-trimethyl-3,6-heptadien-2-ol (4.4%), camphene (3.2%), artemisia alcohol (3.2%)	HP-5 MS capillary column (30 m × 0.25 mm i.d. 0.25 μm film thickness)	Turkish	(Azaz et al., 2009)
A. schischkinii Sosn.	Caryophyllene oxide (17.5%), spathulenol (9.1%), *p*-cymene (8.5%), *(E)*-nerolidol (6.2%), caryophylladienol II (4.9%)	Innowax FSC column (60 m × 0.25 mm, 0.25 μm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. schischkinii Sosn.	Eucalyptol (31.0%), camphor (20.0%), borneol (7.2%), caryophylla-4(14),8(15)-dien-5-ol (3.5%), *β*-pinene (2.9%),	HP-5 MS capillary column (30 m x 0.25 mm, film thickness 0.25 μm)	Turkish	(Donmez et al., 2005)
A. setacea Waldst. & Kit.	*α*-Bisabolon oxide A (27.0%), hexadecanoic acid (16.4%), *α*-bisabolol oxide B (5.7%), *α*-bisabolol (4.8%), camphor (4.1%)	Innowax FSC column (60 m × 0.25 mm, 0.25 μm film thickness)	Turkish	(Turkmenoglu et al., 2015)

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Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
A. setacea Waldst. & Kit.	Eucalyptol (18.5%), sabinene (10.8%), camphor (5.3%), *α*-pinene (3.9%), terpinen-4-ol (3.5%),	HP-5 MS (Crosslinked 5% PH ME Siloxane) capillary column (30 m, 0.25 mm i.d., 0.25 µm film thickness)	Turkish	(Ünlü et al., 2002)
A. sieheana Stapf	Camphor (24.0%), artemisia alcohol (20.1%), eucalyptol (14.4%), *α*-terpineol (3.6%), terpinen-4-ol (2.9%)	Innowax FSC column (60 m ×0.25 mm i.d., film thickness 0.25 µm)	2 different Counties of Antalya	(Kürkçüoğlu et al., 2003)
	Eucalyptol (23.8%), *α*-pinene (12.3%), piperitone (10.3%), terpinen-4-ol (5.3%), camphor (4.2%)			
A. sieheana Stapf	Camphor (43.4), artemisia ketone (26.0%), eucalyptol (6.3%), camphene (4.8%), artemisia alcohol (2.5%)	FFAP capillary column (50 m × 0.32 mm i.d., film thickness 1.2 µm)	Turkish.	(Albayrak, 2013)
A. sieheana Stapf	(1S)(-)-Camphor (39.9%), eucalyptol (15.5%), camphene (8.3%), spathulenol (2.3%), terpinen-4-ol (2.1%)	HP-Innowax FSC Column (60 m x 0.25 mm, 0.25 µm film thickness) and Lipodex E (70% in OV 1701, 25 m x 0.25mm)	Turkish	(Tabanca et al., 2004)
A. sintenisii Hub.-Mor.	Camphor (14.8–63.3%), eucalyptol (12.9–71.4%), *β*-pinene (12.8–34.8%), borneol (10.8–30.0%), piperitone (10.2–57.8%),	HP-5 MS (crosslinked 5% PH ME Siloxane) capillary column (30 m, 0.25 mm i.d., 0.25 µm film thickness)	7 fractions-Sivas-Turkish	(Sökmen et al., 2003)
A. sintenisii Hub.-Mor.	*β*-Eudesmol (26.4%), hexadecanoic acid (22.7%), caryophyllene oxide (7.5%), caryophylladienol II (4.8%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. sivasica Çelik & Akpulat	Eucalyptol (22.1%), *α*-pinene (9.3%), *α*-bisabolol (4.3%), camphor (4.1%), *β*-eudesmol (3.9%),	HP-Innowax FSC column (60 m × 0.25 mm id with 0.25 µm film thickness, Agilent, USA)	Flowers essential oil	(Özek et al., 2018)
	(Z)-*β*-Farnesene (23.9%), decanoic acid (10.1%), *β*-eudesmol (8.0%), tricosane (7.3%), hexadecanoic acid (7.2%),		Flowers SPME	
	Camphor (9.0%), *β*-pinene (6.9%), *α*-pinene (6.7%), eucalyptol (6.7%), *α*-bisabolol (6.6%)		Leaves essential oil	
	(E)-Geranyl acetone (10.5%), *(E)*-*β*-Ionone (10.3%), camphor (10.2%), eucalyptol (9.6%), longiverbenone (7.9%)		Leaves SPME	
	Hexadecanoic acid (15.1%), longiverbenone (14.1%), decanol (12.5%), nonanol (12.1%), (E)-geranyl acetone (9.3%),		Root SPME	
A. talagonica Boiss.	Eucalyptol (27.0%), camphor (20.0%), chrysanthenone (9.0%), isochrysanthenone (5.1%), sabinene (4.4%),	CP Sil5 CB column, (25 m x 0.25 mm film thickness 0.39 µm)	Iranian	(Rustaiyan et al., 1998)
A. taygetea Boiss. & Heldr.	Eucalyptol (26.6%), camphor (25.7%), borneol (6.7%), camphene (3.9%), *α*-terpineol (3.5%)	HP-5 capillary column (30 m × 0.25 mm L, with 0.25 µm film thickness)	Taygetus mountains	(Magiatis et al., 2002)
A. tenuifolia Lam.	Eucalyptol (713), *α*-pinene (653), cadinene isomer (370)-(area)	DB-Wax column (60 m × 0.32 mm with a 0.25 µm film thickness -J &	Leaves	(Dokhani et al., 2005)

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Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
	Eucalyptol (1116), *α*-pinene (933), dl-limonene (532), camphene (352), *β*-terpinene (366), cadinene isomer (333)-(area)	W Scientific, Folsom, CA)	Flowers	
A. tenuifolia Lam.	*Trans*-Borneol (16.5%), germacrene d (10.5%), carvomenthenone (6.8%), *α*-pinene (5.4%), eucalyptol (5.2%)	HP-5MS (60 m × 0.25 mm L, with 0.25 mm film thickness)		(Angourani et al., 2023)
A. tenuifolia Lam.	Isoascaridol (24.3%), eucalyptol (15.5%), *p*-cymene (14.2%), *p*-menthe-1,4-dien-7-ol (9.4%), caryophyllene oxide (5.3%),	HP-88 capillary column (100 m × 250 µm × 0.20 µm film thickness)	Batman-Turkish	(Toncer et al., 2010)
A. teretifolia	Piperitone (21.4%), linalool (19.0%), eucalyptol (6.8%), *α*-terpineol (5.9%), borneol (4.3%)	HP Innowax Capillary (60.0 m × 0.25 mm × 0.25 µm)	Turkish	(Aslan et al., 2009)
A. teretifolia	Eucalyptol (16.1%), camphor (12.7%), *p*-cymene (10.6%), terpinen-4-ol (6.1%), chrysanthenone (4.3%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Afyon-Turkish	(Türkmenoğlu & Demirci, 2020)
A. teretifolia	*δ*-Cadinene (19.0%), limonene oxide (10.1%), alloaromadendrene (6.4%), caryophyllene oxide (5.7%), *trans*-caryophyllene (4.9%)	-	Turkish	(Kocak et al., 2010)
A. teretifolia	Eucalyptol (33.7%), camphor (11.4%), terpinen-4-ol (7.9%), *α*-thujone (5.4%),	Innowax FSC column (60 m x 0.25 mm, 0.25 µm film thickness)	Turkish	(Demirci et al., 2009)
A. teretifolia	Eucalyptol (19.9%), borneol (11.9%), camphor (11.1.3%), thujone (5.1%), sabinene (4.7%)	HP-5 MS (Crosslinked 5% PH ME Siloxane) capillary column (30 m, 0.25 mm i.d., 0.25 µm film thickness)	Turkish	(Ünlü et al., 2002)
A. teretifolia	Eucalyptol (15.9%), borneol (8.1%), camphor (7.0%), t-cadinol (5.9%), *trans*-nerolidol (5.1%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Polatoğlu et al., 2013)
A. vermicularis Trin.	Eucalyptol (29.2%), camphor (25.8%), borneol (5.2%), piperitone (4.5%), camphene (3.8%),	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Polatoğlu et al., 2013)
A. vermicularis Trin.	15-Hexadecanolide (19.6%), camphor (6.7%), heptacosane (6.3%), bornyl acetate (5.1%), chrysanthenyl isovalerate i (4.8%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. vermicularis Trin.	Camphor (32.0%), eucalyptol (29.0%), borneol (4.0%), *α*-pinene (3.7%), camphene (3.3%),	CP Sil5 CB column, (25 m x 0.25 mm film thickness 0.39 µm)	Iranian	(Rustaiyan et al., 1998)
A. wilhelmsii K.Koch	Camphor (8.1–44.9%), fragranol (0.2–43.3%), *α*-pinene (0.8–23.8%), eucalyptol (0.7–20.9%), camphene (0.5-8.0%)	BPX5 column (30 m, 0.25 mm internal diameter, and 0.25 µm film thickness)	Different Counties of Hamedan	(Salehi & Kalvandi, 2025)
A. wilhelmsii K.Koch	Eucalyptol (8.0%), santolinoidol (1) (7.1%), terpinen-4-ol (6.9%), *α*-pinene (6.0%), t-cadinol (2.6%)	DB-5MS column and HP Innowax column	Lebanese	(Fahed et al., 2016)
A. wilhelmsii K.Koch	Camphor (41.3%), caryophylladienol II (6.4%), borneol (6.2%), camphene (6.1%), eucalyptol (4.2%)	Innowax FSC column (60 m × 0.25 mm, 0.25 µm film thickness)	Turkish	(Turkmenoglu et al., 2015)
A. wilhelmsii K.Koch	*α*-Pinene (999), camphene (163), eucalyptol (116), camphor (112)-(area)	DB-Wax column (60 m × 0.32 mm with a 0.25 µm film thickness -J &	Leaves-Region-1	(Dokhani et al., 2005)

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SPME: Solid-phase microextraction

Species	Essential Oil Compositions (Major Components)	Column	Notes	Reference
	α-Pinene (1100), camphene (208), *α*-thujene (184)-(area)	W Scientific, Folsom, CA)	Flowers-Region-1	
	α-Pinene (213)-(area)		Leaves-Region-2	
	α-Pinene (499), unknown (143)-(area)		Flowers-Region-2	
	α-Pinene (381), unknown (111)-(area)		Leaves- Region-3	
	α-Pinene (665), unknown (133)-(area)		Flowers-Region-3	
A. wilhelmsii K.Koch	Camphor (9.9%), eucalyptol (5.7%), (+)-2-bornanone (5.6%), caryophyllene oxide (5.6%), *α*-terpineol (4.5%)	HP-5MS (60 m × 0.25 mm L, with 0.25 µm film thickness)	-	(Angourani et al., 2023)
A. wilhelmsii K.Koch	Camphor (39.6%), artemisia alcohol (17.9%), 2,5,5-trimethyl-3,6-heptadien-2-ol (16.1%), camphor (9.4%), eucalyptol (%7.2%)	HP-5 MS capillary column (30 m × 0.25 mm i.d. 0.25 µm film thickness)	Hakkari-Turkish	(Azaz et al., 2008)
A. wilhelmsii K.Koch	Carvacrol (22.5%), dihydrocarvone (13.2%), linalool (12.0%), eucalyptol (11.4%), camphene (8.3%),	HP-5 MS capillary column (30 m × 0.25 mm i.d. 0.25 µm film thickness)	Iranian	(Alfatemi et al., 2015)
A. wilhelmsii K.Koch	Camphor (46.6%), eucalyptol (14.4%), *cis*-thujone (4.6%), camphene (3.3%), borneol (2.9%),	SGE-BPX5 MS FSC column (30 m x 0.25 mm i.d., film thickness 0.25 µm)	Essential oil	(Çakır et al., 2016)
	Camphor (44.7%), eucalyptol (19.5%), *α*-pinene (6.4%), camphene (5.9%), artemisia alcohol (3.7%)		n-hexane extract	
FSC: Fused silica capillary				
SFE: Supercritical extraction				
SPME: Solid-phase microextraction				

2. MATERIALS AND METHODS

2.1. Plant materials

Plant samples at full bloom were collected in 2024 from different counties of Malatya province in Türkiye. *A. arabica*; A1 was collected from Pütürge County, A2 from Kale County, and A3 from Hekimhan County. *A. teretifolia*; T1 was collected from Pütürge County, T2 from Kale County, and T3 from Yeşilyurt County. The Flora of Türkiye and the East Aegean Islands (Vol. 5) and the Flora of Malatya Province were used as sources for plant identification (Huber-Morath, 1975; Karakuş, 2016). The collected plant samples were dried in the shade in a dry and cool environment. The dried plant samples were ground using a mill when needed. Herbarium specimens were prepared from the plant samples collected from each location and transferred to the herbarium of the Faculty of Pharmacy at İnönü University with the collector codes *A. teretifolia* (TK 1507, TK 1511, and TK 1512) and *A. arabica* (TK 1508, TK 1509, and TK 1510).

2.2. Clevenger distillation for essential oils

When a sufficient amount of plant sample is to be used, it is ground using a mill. Fifty grams of each plant sample were transferred to 1000 mL flasks and filled to no more than half their capacity with distilled water. The essential oils were obtained by subjecting them to 3 hours of distillation using the Clevenger apparatus (Koşar et al., 2007; Kürkçüoglu et al., 1995). Samples to be analyzed using two different devices were obtained separately.

2.3. Determination of essential oils

2.3.1. Laboratory-1

Gas chromatography equipped with a mass spectrometry (GC-MS) system (Shimadzu QP2010, Kyoto, Japan) was used and the compounds were separated using a DB-5MS (60 m ×0.25 mm ×0.25 μm; J&W Scientific, Folsom, CA, USA) capillary columns. Helium was used as a carrier gas at flow rate of 1 mL/min. Identification of the essential oil and chromatographic conditions were the same methodology as

described in Gökçe et al. (2021)(Gökçe et al., 2021). Mass spectra of each compound were compared and matched with NIST and Wiley libraries and 35 authentic standards of volatiles were used at the same chromatographic conditions for confirmation. The essential oil compounds, the relative retention indices (RRI) and relative percentages (%) of the essential oils are given (Table 1). Each measurement was repeated at least three times to calculate the standard deviation.

2.3.2. Laboratory-2

The essential oils obtained by distillation were analysed at the Scientific and Technological Research Centre (IBTAM). Gas chromatograph equipped with an an 19091N-136 HP-INNOWAX column (60 m x 0.25 mm i.d., 0.25 µm film thickness) and GC-MS analyses were carried with the GC system of Agilent Technologies 6890N Network system gas chromatograph equipped with an Agilent Technologies 5973 inert Mass Selective Detector (Agilent G3180B Two-Ways Splitters with Makeup gas) in the electron impact mode (70eV) by the method given by Arabacı et al. (2020) (Arabacı et al., 2020). Injector and detector temperatures were at 250°C. The oven temperature was linearly raised from 60 to 250°C at a rate of 5°C/min, then kept constant at 250°C for 20 min. Helium was used as the carrier gas at a flow rate of 1.7 mL/min. The library of FLAVOR2, NIST05a, NIST08 and WILEY8 were used. Relative indices calculated by reference of linear alkanes series of C8-C35. Since only one injection was made, standard deviation was not calculated. The essential oil compounds, the relative retention indices (RRI) and relative percentages (%) of the essential oils are given (Table 2).

2.4. Statistical analysis and data plotting

Statistical analyses were performed using GraphPad Prism software (version 10) to determine quantitative differences in the essential oil components between *A. arabica* and *A. teretifolia*. The data were compared using Two-way ANOVA or multiple unpaired t-tests for each compound. A p-value of less than 0.05 was considered statistically significant. Proportion of variance and PC scores graphics were generated with GraphPad Prism. Biplot graphics were generated with PAST 4.13 (PAleontological STatistics). The Z-scores were calculated with Microsoft Office Professional Plus 2021 Excel programs. Z-score formula: $z = (x - \mu) / \sigma$ (Curtis et al., 2016). Where: z = Z-score; x = the value being evaluated; µ = the mean; σ = the standard deviation. Heat map generated with ClustVis 2.0 (https://biit.cs.ut.ee/clustvis/)

3. RESULTS

Significant differences exist in the essential oil composition among *Achillea* species. While eucalyptol and camphor are predominant in some species, compounds such as *α*-pinene, *β*-pinene, or germacrene D are found in higher proportions in others. *A. arabica* has been found to have a different essential oil composition than *A. teretifolia* (Tables 2 & 3). These differences may be related to the genetic structure of the species, the geographical region in which they grow, and environmental factors. Considering that there are approximately 60 taxa in the flora of Türkiye and that a significant portion of these are endemic, it is important to examine the essential oil compositions of these species in detail (Huber-Morath, 1975).

3.1. Laboratory-1 analysis results

As a result of Laboratory-1 analyses, a total of 112 essential oil were detected in samples collected from three different locations of the species *A. arabica* and *A. teretifolia*. Descriptive statistics indicate significant differences in abundance between both species and locations (Table 2).

3.1.1. *A. arabica* essential oil profile

A total of 73 essential oil were identified in *A. arabica* samples. The average of the most dominant compounds in the general profile of the species was determined to be: camphor (11.97%), eucalyptol (6.77%), borneol (6.17%), and *trans*-2,7-dimethyl-4,6-octadien-2-ol (5.53%). The ratios of these compounds were found to vary depending on the location. For example, the camphor ratio was 6.2% at location A1, while it reached 16.5% at location A2 (Table 2).

3.1.2. *A. teretifolia* essential oil profile

A total of 78 essential oil were identified in *A. teretifolia* samples. The compounds with the highest average percentages were identified as eucalyptol (10.97%), piperitone (9.43%), camphor (6.13%), *β*-eudesmol (5.37%), and 4-terpineol (5.27%). It was observed that the ratios of piperitone (6.0-12.2%) and *β*-eudesmol (2.3–9.2%) compounds could vary depending on the location (Table 2).

3.1.3. Chemical differences between species

When comparing the chemical profiles of the two species, certain compounds were found to be distinctive for each species. Compounds found only in *A. arabica*: *β*-cadinene, *γ*-eudesmol, cedr-8-ene, davana ether isomers, davana furan, geranyl isovalerate, germacrene-D, *trans*-

2,7-dimethyl-4,6-octadien-2-ol, *trans*-pinocarveol, *β*-thujone. Compounds found only in *A. teretifolia*: *α*-terpinene, *α*-terpinolene, *γ*-cadinene, bergamotol, isocaryophyllen, longifolenaldehyde menth-2-en-1-ol, neo-allo-ocimene, nerolidol, sabinene, and *trans*-*β*-ionone (Table 2).

Both species share eucalyptol, which is present at a higher average level in *A. teretifolia* (10.97%) than in *A. arabica* (6.77%), while camphor shows the opposite trend (11.97% in *A. arabica*, 6.13% in *A. teretifolia*) (Table 2).

Table 2
Essential oil in *A. arabica* and *A. teretifolia* collected from three different locations Laboratory-1 using a GC-MS system equipped with an DB-5MS column

		A. arabica						*A. teretifolia*					
		A1		A2		A3		T1		T2		T3	
RRI	Compound name	Mean ± Std		Mean ± Std		Mean ± Std		Mean ± Std		Mean ± Std		Mean ± Std	
907	Santolina triene	ND		0.9 ±	0.0	1.0 ±	0.0	1.1 ±	0.0	ND		0.4 ±	0.0
935	*α*-Thujene	ND		ND		ND		ND		0.8 ±	0.0	0.6 ±	0.0
937	*α*-Pinene	0.5 ±	0.0	1.4 ±	0.0	1.5 ±	0.0	1.3 ±	0.0	1.8 ±	0.1	0.8 ±	0.0
952	Camphene	0.5 ±	0.0	2.3 ±	0.0	2.6 ±	0.0	1.5 ±	0.0	2.1 ±	0.1	0.8 ±	0.0
957	Thuja-2,4 (10)-diene	ND		0.4 ±	0.0	0.3 ±	0.0	ND		ND		ND	
974	Sabinene	ND		ND		ND		0.9 ±	0.0	0.7 ±	0.0	1.3 ±	0.1
978	*β*-Pinene	ND		0.5 ±	0.0	0.5 ±	0.0	1.9 ±	0.0	1.4 ±	0.0	0.9 ±	0.0
1001	Yomogi alcohol	ND		0.6 ±	0.0	0.5 ±	0.0	ND		ND		ND	
1003	*α*-Phellandrene	ND		ND		ND		1.4 ±	0.0	ND		ND	
1017	*α*-Terpinene	ND		ND		ND		2.4 ±	0.0	1.6 ±	0.0	2.0	0.0
1021	*trans*-2,7-Dimethyl-4,6-octadien-2-ol	2.9 ±	0.2	**10.3±**	**0.0**	7.6 ±	0.0	ND		ND		ND	
1022	*p*-Cymene (Cymol)	0.6 ±	0.0	1.3 ±	0.0	1.6 ±	0.0	3.9 ±	0.0	2.3 ±	0.0	1.2	0.0
1029	Sylvestrene	ND		ND		ND		ND		1.0 ±	0.1	ND	
1030	*β*-Phellandrene	ND		ND		ND		0.3 ±	0.0	ND		0.2	0.2
1031	1,8-Cineole (Eucalyptol)	3.9 ±	0.1	**8.7 ±**	**0.1**	**7.7 ±**	**0.0**	**11.7±**	**0.0**	**11.2**	**0.3**	**10.0**	**0.2**
1036	dl-Limonene	ND		0.2 ±	0.2	0.5 ±	0.0	ND		ND		ND	
1066	*cis*-Sabinene hydrate	ND		ND		ND		ND		ND		0.6 ±	0.0
1066	*γ*-Terpinene	ND		ND		ND		ND		ND		3.1	0.1
1069	Artemisia ketone	ND		1.5 ±	0.0	2.5 ±	0.0	ND		ND		ND	
1075	*trans* Sabinene hydrate	2.0 ±	0.2	ND		ND		0.9 ±	0.0	0.3 ±	0.0	1.0	0.0
1081	Butanoic acid, 3-hexenyl ester, *(Z)*-	ND		ND		ND		0.9 ±	0.0	ND		ND	
1091	Artemisia alcohol	ND		0.3 ±	0.0	ND		ND		ND		ND	
1103	*α*-Terpinolene	ND		ND		ND		1.2 ±	0.0	0.8 ±	0.0	1.0	0.0
1114	Linalool	1.7 ±	0.1	3.3 ±	0.0	3.1 ±	0.0	1.4 ±	0.0	4.8 ±	0.0	ND	
1115	Hotrienol	0.2 ±	0.2	ND		ND		ND		0.9 ±	0.0	ND	
1117	Butanoic acid, 3-methyl-, 3-methylbutyl ester	ND		ND		ND		1.0 ±	0.0	ND		ND	

		A. arabica						*A. teretifolia*					
		A1		A2		A3		T1		T2		T3	
1117	Pentyl 3-methylbutanoate	ND		ND		ND		0.8 ±	0.0	ND		0.5 ±	0.0
1120	*β*-Thujone	2.1 ±	0.1	2.0 ±	0.0	1.1 ±	0.0	ND		ND		ND	
1123	Menth-2-en-1-ol	ND		ND		ND		1.8 ±	0.0	1.0 ±	0.0	1.4 ±	0.0
1124	*α*-Campholene aldehyde	ND		0.6 ±	0.0	0.5 ±	0.0	ND		ND		ND	
1140	*trans*-Pinocarveol	1.0 ±	0.1	0.6 ±	0.0	0.5 ±	0.0	ND		ND		ND	
1143	Neo-allo-ocimene	ND		ND		ND		1.2 ±	0.1	0.8 ±	0.0	1.4 ±	0.1
1144	*trans*-Verbenol	ND		ND		0.5 ±	0.0	ND		ND		ND	
1146	Camphor	**6.2 ±**	**0.3**	**16.5±**	**0.2**	**13.2±**	**0.0**	3.4 ±	0.1	**11.6±**	**0.2**	3.4 ±	0.1
1158	Nerol oxide	ND		0.4 ±	0.0	0.8 ±	0.0	ND		ND		ND	
1159	*trans*-Chrysanthemol	ND		0.7 ±	0.2	0.6 ±	0.0	1.8 ±	0.0	0.6 ±	0.0	0.5 ±	0.0
1160	Verbenol	2.5 ±	0.1	2.1 ±	0.0	2.3 ±	0.0	ND		ND		1.1	0.0
1160	Pinocarvone	ND		ND		ND		ND		0.4 ±	0.0	ND	
1165	Borneol	**6.5 ±**	**0.3**	**6.2 ±**	**0.0**	**5.8 ±**	**0.0**	4.5 ±	0.1	2.8 ±	0.0	3.4 ±	0.1
1177	Terpinen-4-ol	0.5 ±	0.0	1.4 ±	0.1	0.9 ±	0.0	**6.4 ±**	**0.1**	4.9 ±	0.0	4.5 ±	0.1
1183	*p*-Cymen-8-ol	ND		0.4 ±	0.0	ND		0.1 ±	0.1	ND		ND	
1189	*α*-Terpineol	0.7 ±	0.0	1.5 ±	0.0	1.0 ±	0.0	3.9 ±	0.1	3.4 ±	0.0	3.0 ±	0.1
1229	*trans*-Piperitol	2.7 ±	2.2	ND		ND		ND		0.5 ±	0.0	1.0	0.0
1232	*trans*-3(10)Caren-2-ol	1.2 ±	1.0	ND		ND		ND		ND		0.2	0.1
1235	Myrtenol	0.9 ±	0.0	0.6 ±	0.0	0.5 ±	0.0	1.3 ±	0.0	0.8 ±	0.0	ND	
1236	*trans*-Myrtanol	ND		ND		ND		1.5 ±	0.1	ND		ND	
1249	Piperitone	2.1 ±	0.1	3.6 ±	0.0	3.0 ±	0.0	**12.2±**	**0.6**	**6.0 ±**	**0.0**	**10.1**	**0.2**
1261	*trans*-Carveol	1.6 ±	1.3	0.6 ±	0.1	ND		0.4 ±	0.0	0.2 ±	0.1	ND	
1274	Phellandral	ND		ND		ND		ND		0.3 ±	0.0	ND	
1300	Endobornyl acetate	**5.8 ±**	**0.3**	3.3 ±	0.0	4.0 ±	0.0	0.7 ±	0.0	ND		0.5 ±	0.0
1345	Thymol	ND		ND		ND		0.4 ±	0.0	ND		ND	
1345	*p*-Cymen-7-ol	ND		0.4 ±	0.0	ND		ND		ND		ND	
1352	4-Terpinenyl acetate	ND		ND		ND		1.2 ±	0.0	0.2 ±	0.1	ND	
1367	Chavibetol	ND		ND		ND		0.5 ±	0.4	0.5 ±	0.0	0.9 ±	0.0

		A. arabica						*A. teretifolia*					
		A1		A2		A3		T1		T2		T3	
1371	Eugenol	ND		ND		ND		0.5 ±	0.4	ND		ND	
1420	*β*-Caryophyllene	ND		ND		0.2 ±	0.1	ND		0.6 ±	0.0	ND	
1428	Methyleugenol	ND		ND		ND		ND		1.0 ±	0.2	ND	
1430	*α*-Ionone	1.5 ±	0.1	ND		ND		ND		ND		ND	
1433	*trans*-Caryophyllene	ND		ND		ND		ND		0.2 ±	0.1	0.2 ±	0.2
1445	*β*-Farnesene	0.4 ±	0.3	ND		0.4 ±	0.0	ND		ND		ND	
1450	*α*-Longipinene	0.5 ±	0.4	ND		ND		ND		ND		ND	
1466	Davana furan	0.7 ±	0.1	1.2 ±	0.0	1.4 ±	0.0	ND		ND		ND	
1479	Cedr-8-ene	0.4 ±	0.3	0.4 ±	0.0	0.6 ±	0.0	ND		ND		ND	
1486	*trans*-*β*-Ionone	ND		ND		ND		0.6 ±	0.0	0.8 ±	0.0	1.0 ±	0.0
1511	2-Isopropenyl-4a,8-dimethyl-1,2,3,4,4a,5,6,7 -octahydro-naphthalene	ND		ND		0.3 ±	0.0	ND		ND		ND	
1517	Germacrene-D	3.7 ±	0.4	1.8 ±	0.1	2.4 ±	0.0	ND		ND		ND	
1521	Davana ether 1	0.9 ±	0.7	1.0 ±	0.0	1.5 ±	0.0	ND		ND		ND	
1526	Isocaryophyllen	ND		ND		ND		0.5 ±	0.0	0.4 ±	0.0	0.9 ±	0.1
1529	*γ*-Elemene	ND		0.9 ±	0.0	1.4 ±	0.0	ND		ND		ND	
1537	Nerolidol	ND		ND		ND		0.8 ±	0.0	1.9 ±	0.0	2.0 ±	0.1
1540	*α*-Bisabolene	0.7 ±	0.0	ND		0.2 ±	0.1	ND		ND		ND	
1540	Davana ether 2	2.6 ±	0.1	2.3 ±	0.1	3.3 ±	0.0	ND		ND		ND	
1544	*γ*-Cadinene	ND		ND		ND		1.4 ±	0.1	1.2 ±	0.0	1.6 ±	0.0
1555	*β*-Cadinene	0.5 ±	0.0	0.3 ±	0.0	0.4 ±	0.0	ND		ND		ND	
1570	*α*-Calacorene	0.7 ±	0.1	ND		ND		ND		ND		ND	
1583	Davana ether 3	0.8 ±	0.1	1.1 ±	0.1	1.6 ±	0.0	ND		ND		ND	
1590	Davanone	ND		0.4 ±	0.0	0.7 ±	0.0	ND		ND		ND	
1591	Viridiflorol	0.7 ±	0.0	ND		0.5 ±	0.1	ND		ND		ND	
1602	Geranyl isovalerate	3.0 ±	0.4	1.6 ±	0.1	2.0 ±	0.0	ND		ND		ND	
1606	Diethyl phthalate	2.1 ±	0.3	ND		ND		ND		ND		ND	

		A. arabica						*A. teretifolia*					
		A1		A2		A3		T1		T2		T3	
1610	Carotol	ND		ND		ND		0.4 ±	0.0	ND		0.4 ±	0.0
1613	Guaiol	ND		ND		ND		0.4 ±	0.0	ND		0.4 ±	0.0
1625	Daucol	0.2 ±	0.1	ND		ND		0.5 ±	0.1	ND		ND	
1627	Cedrol	ND		ND		ND		0.3 ±	0.1	ND		ND	
1640	Bergamotol	ND		ND		ND		0.6 ±	0.1	0.7 ±	0.0	0.7 ±	0.0
1642	*γ*-Eudesmol	1.9 ±	0.2	1.1 ±	0.0	1.2 ±	0.0	ND		ND		ND	
1646	Tetracyclo[6.3.2.0(2,5).0(1,8)]tridecan-9-ol, 4,4-dimethyl-	0.5 ±	0.0	0.7 ±	0.1	1.5 ±	0.0	1.8 ±	0.0	**6.0 ±**	**0.0**	**6.7 ±**	**0.1**
1650	Spathulenol	3.4 ±	0.3	1.3 ±	0.1	1.8 ±	0.1	0.5 ±	0.0	1.8 ±	0.2	0.6 ±	0.2
1653	Cadinol (*α*, epi-)	1.7 ±	0.4	1.0 ±	0.1	1.5 ±	0.0	**5.8 ±**	**0.2**	3.3 ±	0.3	4.8 ±	0.1
1663	*β*-Eudesmol	**5.0 ±**	**0.2**	2.5 ±	0.2	2.8 ±	0.0	2.3 ±	1.8	4.6 ±	0.2	**9.2 ±**	**0.1**
1667	Muurolol (*α*, epi-)	2.8 ±	0.3	ND		ND		ND		ND		ND	
1672	*α*-Bisabolol oxide B	ND		0.2 ±	0.1	1.4 ±	0.0	ND		ND		ND	
1675	Valeranone	1.0 ±	0.1	0.5 ±	0.0	0.5 ±	0.0	0.5 ±	0.0	0.4 ±	0.0	ND	
1677	2-Propenal, 3-(2,6,6-trimethyl-1-cyclohexen-1-yl)	ND		ND		0.8 ±	0.0	ND		ND		ND	
1679	Murolan-3,9(11)-diene-10-peroxy	ND		ND		ND		0.3 ±	0.2	0.1 ±	0.1	0.2 ±	0.2
1680	Androstan-17-one, 3-ethyl-3-hydroxy-, (5.*α*.)-	0.9 ±	0.1	0.5 ±	0.0	ND		0.6 ±	0.0	1.8 ±	0.3	0.8 ±	0.0
1694	Alloaromadendrene oxide	ND		ND		ND		ND		ND		1.2 ±	0.0
1695	Androstenedione	ND		ND		ND		0.7 ±	0.0	ND		ND	
1706	Caryophyllene oxide	3.1 ±	0.3	2.4 ±	0.4	2.7 ±	0.0	3.8 ±	0.2	2.5 ±	0.3	4.1 ±	0.7
1716	*β*-Santalol	ND		ND		ND		ND		0.3 ±	0.0	ND	
1731	Ledane	ND		ND		ND		0.2 ±	0.1	ND		0.5 ±	0.0
1761	*cis*-Lanceol	ND		ND		ND		ND		ND		0.2 ±	0.1
1808	Longifolenaldehyde	ND		ND		ND		1.7 ±	0.1	2.1 ±	0.0	2.4 ±	0.0
1813	6,10,14-trimethyl-2-Pentadecanone	**5.0 ±**	**0.2**	1.3 ±	0.2	1.5 ±	0.0	0.9 ±	0.0	1.4 ±	0.0	1.0 ±	0.0
1816	Hexadecanal	0.6 ±	0.1	ND		ND		0.6 ±	0.0	ND		ND	
1827	15-Hexadecanolide	4.2 ±	0.1	ND		ND		ND		ND		ND	

		A. arabica						*A. teretifolia*					
		A1		A2		A3		T1		T2		T3	
1827	18-Nonadecenoic acid	ND		1.3 ±	0.1	1.5 ±	0.0	2.8 ±	0.1	3.2 ±	0.1	3.5 ±	0.1
1920	Methyl palmitate	0.6 ±	0.0	ND		ND		ND		ND		ND	
1976	Oleic acid	ND		ND		ND		ND		0.7 ±	0.0	0.8 ±	0.1
2011	Phytol	0.7 ±	0.1	0.6 ±	0.0	0.6 ±	0.0	0.4 ±	0.0	0.6 ±	0.0	0.2 ±	0.2
2044	9,12-Octadecadien-1-ol, (Z,Z)-	2.3 ±	0.1	ND		ND		ND		0.1 ±	0.1	0.2 ±	0.1
2044	Methyl linoleate	ND		1.3 ±	0.1	2.0 ±	0.0	ND		ND		ND	

A. arabica; **A1** was collected from Pütürge County, **A2** from Kale County, and **A3** from Hekimhan County. *A. teretifolia*; **T1** was collected from Pütürge County, **T2** from Kale County, and **T3** from Yeşilyurt County.

RRI

Relative retention indices experimentally determined on a DB-5MS column relative to the Rt of n-alkanes (C8-C35); the compounds are listed in the order of elution.

Compound identification: RI and mass spectra mass spectra (MS) data compared against commercially available MS

Mean ± Std

Mean and standard deviation of relative percentages (%) (n = 3)

ND

Not Detected

3.2. Laboratory-2 analysis results

As a result of Laboratory-2 analyses, a total of 113 essential oil were detected in samples collected from three different locations of the species *A. arabica* and *A. teretifolia* Descriptive statistics indicate significant abundance differences between both species and locations (Table 3).

3.2.1. *A. arabica* essential oil profile

A total of 81 essential oil were identified in *A. arabica* samples. The average of the most dominant compounds in the general profile of the species were bisabolol oxide A (11.97%), palmitic acid (11.43%), *α*-bisabolone oxide A (6.2%), eucalyptol (5.73%), camphor (5.4%), and piperitone (5.00%) (Table 3).

3.2.2. *A. teretifolia* essential oil profile

A total of 71 essential oil were identified in *A. teretifolia* samples. The compounds with the highest average percentages were identified as eucalyptol (14.03%), camphor (12.07%), and piperitone (10.43%) (Table 3).

3.2.3. Chemical differences between species

When comparing the chemical profiles of the two species, some compounds were found to be species-specific. Compounds found only in *A. arabica* were bisabolol oxide A and bisabolone oxide A. Compounds found only in *A. teretifolia* were *α*-terpinolene, *α*-terpinene, *β*-pinene, and allo-aromadendrene (Table 3).

Eucalyptol, which is common to both species, was found at a higher average in A. teretifolia (14.03%) than in *A. arabica* (5.73%), while camphor, unlike in Laboratory-1, is again high in *A. teretifolia* (5.4% in *A. arabica*, 12.07% in *A. teretifolia*) (Table 3). The compound

piperitone was also commonly found and was higher in *A. teretifolia* (5.0% in *A. arabica*, 10.43% in *A. teretifolia*). This situation showed that the ratios of the dominant compounds could change significantly depending on the device conditions.

Table 3
Essential oil in *A. arabica* and *A. teretifolia* collected from 3 different locations was analyzed in Laboratory-2 using a GC-MS system equipped with an HP-INNOWAX column

RRI	Compound name	*A. arabica*			*A. teretifolia*		
		A1	A2	A3	T1	T2	T3
1022	*α*-Pinene	ND	0.8	ND	0.9	1.8	2.1
1042	Santolina triene	ND	ND	ND	ND	ND	0.9
1078	Camphene	ND	1.1	ND	0.6	1.9	1.3
1103	*β*-Pinene	ND	ND	ND	0.7	0.6	1.3
1121	Sabinene	ND	ND	ND	0.5	ND	0.6
1126	Verbenene	ND	0.4	ND	ND	ND	ND
1191	*α*-Terpinene	ND	ND	ND	1.8	0.6	1.9
1211	Limonene	ND	ND	ND	ND	0.7	ND
1253	1,8-Cineole (Eucalyptol)	0.5	**13.2**	3.5	**14.9**	**12.1**	**15.1**
1254	1,6-Dimethylhepta-1,3,5-triene	ND	ND	ND	0.5	ND	0.2
1256	*γ*-Terpinene	ND	0.2	ND	2.9	1.4	3.0
1279	*p*-Cymene	ND	1.5	ND	1.2	1.2	2.7
1289	*α*-Terpinolene	ND	ND	ND	1.0	0.5	0.9
1301	2-Methyl butyl isovalerate	ND	ND	ND	ND	ND	0.3
1359	1,5-Heptadien-4-one, 3,3,6-trimethyl-	ND	ND	3.4	0.4	ND	ND
1405	Yomogi alcohol	ND	ND	0.4	ND	ND	ND
1408	Cyclohexene, 3-methyl	ND	ND	0.9	ND	ND	ND
1410	Methyl isobutylacetylene	ND	3.3	ND	ND	ND	ND
1438	Thujone	0.5	0.4	ND	ND	ND	ND
1451	*β*-Thujone	ND	0.8	ND	ND	ND	ND
1472	*cis*-*β*-Terpineol	ND	ND	ND	0.5	ND	0.2
1478	Neroloxide	ND	ND	1.4	ND	ND	ND
1496	Copaene	ND	ND	ND	ND	0.3	ND
1532	Camphor	0.2	**12.2**	3.8	3.7	**26.4**	**6.1**
1557	Linalool	ND	0.3	ND	0.6	3.9	1.8
1573	*p*-Menth-2-en-1-ol	ND	0.3	ND	1.2	0.3	1.1
1584	Pinocarvone	0.5	ND	ND	ND	ND	0.2
1585	Verbenyl acetate	ND	0.6	ND	ND	ND	ND
1594	L-*α*-Bornyl acetate	ND	2.3	1.4	0.5	ND	ND
1610	Terpinen-4-ol	ND	0.5	0.6	4.4	3.0	5.0
1614	Hotrienol	0.2	0.2	ND	ND	0.8	ND
1626	Tricyclo[2.2.1.0(2,6)]heptane, 1,7-trimethyl-	ND	ND	ND	ND	ND	0.5
1637	2-Cyclohexen-1-ol, 1-methyl-4-(1-methylethyl)-, *cis*-	ND	0.3	ND	0.9	ND	0.8
1649	Bicyclo[3.1.1]hept-2-ene-2-carboxaldehyde, 6,6-dimethyl-	ND	0.3	ND	ND	ND	ND
1652	Bicyclo[3.1.0]hexan-2-one, 5-(1-methylethyl)-	ND	0.3	ND	ND	ND	ND

RRI	Compound name	*A. arabica*			*A. teretifolia*		
		A1	A2	A3	T1	T2	T3
1660	Allo-aromadendrene	ND	ND	ND	0.9	0.3	0.7
1664	*cis*-Verbenol	ND	0.9	ND	ND	ND	ND
1665	*trans*-Pinocarveol	0.7	ND	ND	ND	ND	ND
1669	*(E)-β*-Farnesene	1.0	0.5	ND	ND	ND	ND
1686	*Δ*-Terpineol	ND	0.3	ND	0.5	ND	0.8
1689	*α*-Terpineol	ND	0.7	0.3	1.2	2.0	5.3
1691	*β*-Citral	0.4	ND	0.9	ND	ND	ND
1692	*trans*-Piperitol	ND	ND	ND	1.9	ND	ND
1692	*cis*-Chrysanthemol	ND	2.4	ND	ND	ND	1.6
1695	Isoborneol	1.1	3.6	3.4	3.1	0.6	ND
1716	Verbenone	ND	1.1	0.6	ND	ND	ND
1737	*γ*-Campholenol	ND	ND	ND	ND	0.6	ND
1738	*p*-Mentha-1,5-dien-8-ol	0.8	1.3	1.0	ND	ND	0.4
1743	Piperitone	0.3	**10.9**	3.8	**13.7**	1.1	**16.5**
1756	Isocyclocitral	ND	4.0	ND	1.0	ND	ND
1767	*γ*-Cadinene	ND	ND	ND	1.3	0.7	1.0
1775	Davana Furan	ND	ND	4.8	ND	ND	ND
1804	Cuminaldehyde	ND	0.3	ND	ND	ND	ND
1811	1,6,6-trimethyl-3-methylene-1,4-cyclohexadiene	ND	0.7	ND	ND	ND	ND
1864	*p*-Cymen-8-ol	ND	0.4	ND	ND	ND	ND
1961	Davana ether 1	ND	ND	3.7	0.9	ND	ND
1975	Davana ether 2	ND	ND	4.4	1.2	ND	ND
1978	Davana ether 3	ND	ND	3.6	0.7	ND	ND
2008	Caryophyllene oxide	ND	ND	ND	4.1	3.6	3.6
2028	Methyl eugenol	ND	ND	ND	ND	ND	0.6
2045	Nerolidol	ND	ND	ND	ND	0.9	ND
2059	Octanoic Acid	ND	1.6	1.3	1.1	ND	ND
2098	*trans*-3-Pinene-2-ol	ND	1.7	1.3	ND	ND	ND
2099	Valeranone	ND	ND	ND	ND	ND	0.8
2104	Oxo-T-cadinol	1.4	ND	ND	ND	ND	ND
2124	Spathulenol	4.3	1.4	2.2	ND	ND	0.7
2127	Heptan-2-ol, 5-(2-tetrahydrofurfuryl)-	ND	ND	ND	ND	ND	0.9
2133	2-Pentadecanone, 6,10,14-trimethyl	ND	ND	2.5	ND	1.2	ND
2301	Isophytol	ND	ND	ND	1.8	ND	1.3
2137	Bisabolol oxide B	1.0	2.7	ND	ND	ND	ND
2183	Bicyclosesquiphellandrene	ND	ND	ND	ND	**5.3**	ND
2185	*Δ*-Cadinene	ND	ND	ND	**7.6**	ND	ND

RRI	Compound name	*A. arabica*			*A. teretifolia*		
		A1	A2	A3	T1	T2	T3
2186	*α*-Bisabolone oxide A	**15.0**	3.6	ND	ND	ND	ND
2187	*β*-Cadinene	ND	ND	ND	ND	ND	**5.4**
2188	Nonanoic acid	ND	ND	1.8	ND	ND	ND
2201	*α*-Cadinol	0.4	ND	ND	ND	1.0	1.0
2206	Thymol	ND	0.4	ND	ND	ND	ND
2210	*(Z)*-3-Ethyl-2-methyl-1,3-hexadiene	ND	ND	1.7	ND	ND	ND
2218	Ledane	ND	ND	0.8	ND	ND	ND
2232	*α*-Bisabolol	0.2	ND	ND	ND	ND	ND
2237	Carvacrol	ND	ND	1.5	ND	ND	ND
2238	Oxacyclotridecan-2-one	1.1	1.6	ND	ND	ND	ND
2241	15-hexadecanolide	ND	ND	ND	2.5	1.7	ND
2242	*β*-Eudesmol	0.4	1.5	1.2	4.7	2.4	4.2
2255	Isoaromadendrene epoxide	ND	ND	0.5	ND	0.9	0.8
2279	Davanone	ND	ND	1.6	ND	ND	ND
2295	*n*-Decanoic acid	3.5	1.4	**5.5**	1.8	1.3	0.7
2315	Caryophylla-4(12),8(13)-dien-5-*β*-ol	ND	ND	ND	1.1	1.1	ND
2316	3,5-dimethylbenzyl alcohol	ND	ND	ND	ND	ND	1.1
2317	10,10-Dimethyl-2,6-dimethylenebicyclo[7.2.0]undecan-5*β*-ol	0.7	ND	ND	3.3	3.6	ND
2318	Tetracyclo[6.3.2.0(2,5).0(1,8)]tridecan-9-ol, 4,4-dimethyl-	ND	ND	ND	ND	ND	3.1
2326	Caryophylla-3,8(13)-dien-5*β*-ol	ND	ND	ND	1.0	ND	ND
2329	*p*-Allylphenol	ND	ND	ND	0.5	ND	0.6
2347	7R,8R-8-Hydroxy-4-isopropylidene-7-methylbicyclo[5.3.1]undec-1-ene	ND	ND	0.6	ND	ND	ND
2371	Caryophyllenol-II	ND	ND	ND	ND	1.6	1.4
2372	Vulgarol B	0.6	ND	ND	ND	ND	ND
2373	Longipinocarveol, *trans*-	ND	ND	0.6	ND	ND	ND
2426	Bisabolol oxide A	**30.8**	**5.1**	ND	ND	ND	ND
2501	Lauric acid	0.7	0.8	1.4	0.4	0.5	ND
2589	Benzoic acid, 2,5-bis(trimethylsiloxy)-, trimethylsilyl ester	1.2	ND	ND	ND	ND	ND
2626	Phytol	0.5	0.5	1.2	0.5	0.7	1.3
2671	Tricyclo[6.3.0.0(1,5)]undecan-10-one, 4-[(2-methoxyethoxy)methoxy]-5-methyl-	ND	ND	ND	ND	0.4	ND
2672	Ambrettolide	0.9	0.9	2.5	0.7	ND	ND
2719	Tetradecanoic acid	3.3	2.4	**5.4**	1.3	2.2	ND
2725	3-Methylheneicosane	3.6	ND	ND	ND	ND	ND
2752	1,5-Cyclododecadiene, (Z,Z)	0.8	ND	ND	ND	ND	ND
2753	Octahydrocyclobuta[c]pentalene	ND	0.4	1.7	ND	ND	ND
2822	Pentadecanoic acid	0.5	0.3	1.1	ND	0.4	ND
2832	1-Phenyloctadecane	0.4	ND	ND	ND	ND	ND

RRI	Compound name	*A. arabica*			*A. teretifolia*		
		A1	A2	A3	T1	T2	T3
2851	Pentadecalactone	ND	ND	0.5	ND	ND	ND
2908	Palmitic acid	**10.2**	**6.8**	**17.3**	4.1	**9.1**	ND
3110	Oleic acid	ND	0.5	1.1	ND	ND	ND
3172	Linoleic acid	ND	ND	2.9	ND	1.2	ND

A. arabica; **A1** was collected from Pütürge County, **A2** from Kale County, and **A3** from Hekimhan County. *A. teretifolia*; **T1** was collected from Pütürge County, **T2** from Kale County, and **T3** from Yeşilyurt County.

RRI

Relative retention indices experimentally determined on a DB-5MS column relative to the Rt of n-alkanes (C8-C35); the compounds are listed in the order of elution.

Compound identification: RI and mass spectra mass spectra (MS) data compared against commercially available MS

ND

Not Detected

3.3. Multivariate statistical analysis and heat map

3.3.1. Heat map of the relative abundance of essential oil jointly identified in devices

The heat map presented in Fig. 1 visualizes the standardized relative abundances (Z-scores) of the identified essential oil. This analysis shows how “significant” or “unusual” each compound in each sample is relative to the average of the entire sample group, rather than just looking at average values. Red represents abundance above the average (positive Z-score), while blue represents abundance below the average (negative Z-score).

3.3.2. Statistical validation of interspecies distinctive markers

Z-score analysis clearly identifies the chemical markers that distinguish the two species. Characteristic compounds for *A. arabica*: As clearly seen in the heat map, davana group compounds (ether 1, 2, 3, furan, davanone) consistently show high negative Z-scores (dark blue color) in these samples (A1, A2, A3), while they are either undetectable (gray) or well below average (red) in *A. teretifolia* samples. For example, in the Laboratory-1 analysis, the Z-score for Davana ether 3 is negative for A3, while it is positive for all T samples. This statistically confirms that Davana compounds are a strong chemical marker for *A. arabica*.

The characteristic compounds of *A. teretifolia*, namely *α*-terpinene, *α*-terpinolene, sabinene and *γ*-cadinene, consistently exhibited high negative Z-scores in these samples (T1, T2 and T3). For example, sabinene's Z-score in Laboratory-1 was negative in T3, but positive in all A samples. This indicates that these compounds chemically define *A. teretifolia*

3.3.3. Identification of location-based significant differences

Z-score analysis highlights significant chemical differences not only between species but also between different locations of the same species. In the Laboratory-1 analysis, the A1 sample was statistically significantly different from all other *A. arabica* samples (A2 and A3) in terms of the 15-hexadecanolide compound ($p < 0.0001$). This indicates that the Pütürge location may have a unique chemical profile in terms of the production of this compound. Similarly, in the Laboratory-1 analysis, the T3 (Yeşilyurt) sample was significantly richer in *β*-eudesmol abundance than the other *A. teretifolia* Samples (Fig. 1). This suggests that the environmental conditions at the T3 location promote the accumulation of this sesquiterpene.

3.3.4. Evaluation of differences between analytical methods

While both GC-MS analyses support general species differentiation, differences in the Z-scores of some compounds are noteworthy. For example, Camphor has the highest Z-score in sample A2 in Laboratory-1, while it has the highest Z-score in sample T2 in Laboratory-2 (Fig. 1). This situation confirms that different chromatographic conditions (Laboratory-1 vs Laboratory-2) can affect the relative

abundances of compounds and therefore highlights the importance of standardizing the analytical method in chemotype (chemical type) determination studies.

A. arabica; A1 was collected from Pütürge County, A2 from Kale County, and A3 from Hekimhan County. *A. teretifolia*; T1 was collected from Pütürge County, T2 from Kale County, and T3 from Yeşilyurt County.

3.3.5. Multivariate Visualization of Species-Specific Essential Oil Profiles Via PCA and Biplot Analysis

Principal Component Analysis (PCA) was applied to the essential oil datasets obtained from both laboratories to visualize species-specific chemical patterns and to evaluate the discriminative power of major and minor volatile components. The PCA score plots from Laboratory-1 (non-polar column) and Laboratory-2 (polar column) demonstrated a clear clustering of *A. arabica* (A1–A3) and *A. teretifolia* (T1–T3) samples (Figs. 2A and 2C). This separation indicates that, despite being collected from relatively close microenvironments, the two species possess distinct chemical signatures that remain consistent across different chromatographic conditions.

The scree plots (Figs. 2B and 2D) showed that the first two principal components (PC1 and PC2) explain a substantial portion of the total variance (PC1 = %46.52, PC2 = %20.71 for Laboratory-1; PC1 = %36.40, PC2 = %21.61 for Laboratory-2) in both laboratories, confirming that the essential oil datasets contain structured, non-random variation. In Laboratory-1, PC1 is dominated by monoterpenes such as camphor, eucalyptol and borneol, whereas PC2 is shaped mainly by several sesquiterpene-related compounds. In Laboratory-2, oxygenated sesquiterpenes (e.g., bisabolol oxide A and *α*-bisabolone oxide A) contribute more strongly to PC1, reflecting the higher sensitivity of the polar column to late-eluting, oxygenated sesquiterpenes.

A. arabica; A1 was collected from Pütürge County, A2 from Kale County, and A3 from Hekimhan County. *A. teretifolia*; T1 was collected from Pütürge County, T2 from Kale County, and T3 from Yeşilyurt County. The color scale shows PC1 values; color usage highlights the distinction.

When creating a Biplot, it was found that there was visual complexity when all compounds were selected. Therefore, the 10 compounds with the highest average in each type showing significant differences were selected (For example, in Laboratory-1, camphor, trans-2,7-dimethyl-4,6-octadien-2-ol, eucalyptol, borneol, endobornyl acetate, *β*-eudesmol, piperitone, davana ether 2, caryophyllene oxide, linalool for A. arabica). The Biplot visualisations showing all the compounds were not excluded either, because the selected compounds could alter some meaningful aspects of the visualisation.

Figure 3 and Fig. 4 from Laboratory-1 (DB-5MS, non-polar column) show a clear separation of the two species and additional location-dependent variation within species. Samples of *A. arabica* (A1–A3) cluster apart from *A. teretifolia* (T1–T3) along the first two principal components, with the A-group oriented toward compounds such as borneol, endobornyl acetate, endobornyl-related esters and trans-2,7-dimethyl-4,6-octadien-2-ol, while the T-group is associated with eucalyptol, piperitone and terpinen-4-ol.

Figure 5 shows the PCA biplot based on selected components, clearly revealing differentiation between species. Figure 6 shows the analysis including all components and reveals location-dependent variations within the same species. The strong positive correlation between components such as bisabolol oxide A, palmitic acid and *α*-bisabolone oxide A with the A series samples and between components such as eucalyptol, piperitone, camphor and terpinen-4-ol with the T series samples supports the key role of these components in species differentiation. Location A1 showed the greatest shift towards bisabolol oxide A and *α*-bisabolone oxide A, emphasising the effect of location differences on the ratio of chemical structures.

Overall, the PCA and biplot analyses confirmed that the two species possess well-defined and robust chemotypic boundaries, intra-specific micro-environmental factors generate measurable but secondary variation, and the reproducibility of results across two laboratories supports the biological validity of the observed chemical patterns. It has been observed that there is not much visual difference between the graphs selected based on averages (Figs. 3 & 5) and the graphs where all compounds are selected (Figs. 4 & 6). These findings underscore the usefulness of multivariate statistical tools in chemotaxonomic evaluations of *Achillea* species and illustrate the ecological drivers shaping essential oil diversity.

3.4. Laboratory comparison

Volatile compounds were detected in samples collected from three different locations of the species *A. arabica* and *A. teretifolia* using different GC-MS devices (Table 2, and 3). Although approximately the same number of compounds were detected on the two different devices, different compounds could be analyzed. This indicates that factors such as the polarity of the column used, the sensitivity of the device, and the analysis conditions affected the results. However, for major compounds such as camphor and eucalyptol both devices detected statistically significant differences between species in the same direction ($p < 0.05$). Laboratory-2 revealed some compounds (e.g.,

α-bisabolol oxide A, *α*-bisabolone oxide A) that were not detected by Laboratory-1 but were present in high abundance. This shows that the instrument/column difference broadened the scope of the chemical profile. The absolute value differences between the instruments are not significant enough to alter the direction of the biological interpretation. However, Laboratory-2 provides additional information for chemotaxonomic evaluations by offering a more detailed and rich profile, particularly for polar compounds.

3.5. Evaluation of inter-device location effect

For major compounds such as camphor, piperitone, and *β*-eudesmol, both devices showed significant differences in the same locations. This indicates that location-based variations can be reliably detected independently of the device, but it also shows variability in the percentages. In Laboratory 1, no significant differences were observed between species at positions T1, T2, T3, A2 and A3. However, a significant difference was observed at position A1 between species. In Laboratory 2, the A1 and A3 samples showed a difference. However, none of these differences were found to be statistically significant ($p > 0.05$).

These results once again highlight the importance of a multifaceted evaluation of analyses. They show that plant samples collected from a single location are insufficient and that the columns and operating conditions of the instruments must also be evaluated when comparing results.

4. DISCUSSION

The results of this study are largely consistent with findings in the literature regarding the volatile components of the *Achillea* sp. (Table 1) and confirm variations between species, locations, and analysis methods. Major components reported in the literature for the species *A. arabica* and *A. teretifolia* (eucalyptol, camphor, piperitone) were predominantly detected in this study using both GC-MS devices. However, the ratios and additional components showed significant differences depending on the location, extraction method, and column type.

In the literature for *A. arabica*, eucalyptol (5.1–42.3%), camphor (3.2–27.5%), piperitone (9.2–34.9%), *p*-cymene (2.5–18.6%), and borneol (3.3–6.5%) have been reported at high levels (Mottaghi et al., 2016; Polatoğlu et al., 2013; Rustaiyan et al., 1998; Toncer et al., 2010). In this study, Laboratory-1 (DB-5MS) results were consistent with the literature in terms of camphor (average 11.97%) and eucalyptol (6.77%), and location variations (e.g., camphor 16.5% in A2) reflected similar environmental effects. Laboratory-2 (HP-Innowax), on the other hand, highlights polar components such as bisabolol oxide A (11.97%) and palmitic acid (11.43%), which is consistent with fatty acids (hexadecanoic acid 11.2%) observed in the literature using polar columns (Innowax FSC) (Turkmenoglu et al., 2015) and bisabolone derivatives observed in the literature when using a polar column (Innowax FSC). While components such as ascaridol (24.2–62.0%) are predominant in Iranian samples in the literature (Istamkulova et al., 2024; Toncer et al., 2010), their absence in Malatya locations may be due to geographical and climatic differences. Variations depending on the extract type are also evident: While amide derivatives are predominant in ethanolic and acetonic extracts in the literature, this study focused on essential oils (Saleh, 2023).

The literature on *A. teretifolia* consists entirely of samples originating from Türkiye and highlights components such as eucalyptol (6.8–33.7%), camphor (7.0-12.7%), piperitone (21.4%), terpinen-4-ol (6.1–7.9%), linalool (19.0%), and borneol (4.3–11.9%) (Aslan et al., 2009; Demirci et al., 2009; Polatoğlu et al., 2013; Türkmenoğlu & Demirci, 2020; Ünlü et al., 2002). In this study, Laboratory-1 showed eucalyptol (10.97%), piperitone (9.43%), and camphor (6.13%); Laboratory-2 showed eucalyptol (14.03%), camphor (12.07%), and piperitone (10.43%) ratios, which showed high correlation with the literature, and it was observed that the polar column (HP-Innowax) increased the detection of camphor and piperitone. While sesquiterpenes such as *δ*-cadinene (19.0%) and alloaromadendrene (6.4%) have been reported in the literature (Kocak et al., 2010), *β*-eudesmol and cadinol derivatives similarly exhibited location-based variations in this study (e.g., *β*-eudesmol 9.2% in T3). The Malatya locations (Pütürge, Kale, Yeşilyurt) showed lower linalool ratios compared to Afyon in the literature, indicating genetic and environmental factors (drought stress).

In general, the dominance of camphor and eucalyptol in the *Achillea* sp. is common in the literature (Angourani et al., 2023; Mohammadhosseini et al., 2017; Shawl et al., 2002), but in this study, the use of two columns confirmed that the non-polar (DB-5MS) column better separated terpenoids, while the polar (HP-Innowax) column better separated oxides and acids-parallel to the use of Innowax and HP-88 in the literature (Toncer et al., 2010; Turkmenoglu et al., 2015). Location effects produced statistically significant differences ($p < 0.05$), as reported in the literature, with Malatya's temperate climate producing more balanced profiles than Iran or other Turkish regions. These variations emphasize the role of column polarity and location in chemotaxonomic classification and also support the antimicrobial potential of plants. Future studies could optimize the pharmaceutical use of *Achillea* sp. by investigating the relationship between these differences and bioactivity.

5. CONCLUSIONS

This study comprehensively analyzed the volatile compound profiles of samples collected from three different locations (Pütürge, Kale, Hekimhan/Yeşilyurt) in the Malatya region of *A. arabica* and *A. teretifolia* species using Laboratory-1 (DB-5MS non-polar column) and Laboratory-2 (HP-Innowax polar column). A total of 112 components were detected in Laboratory-1 and 113 in Laboratory-2, with major components (camphor, eucalyptol, piperitone, *β*-eudesmol, terpinen-4-ol) showing significant variations based on species and location. Camphor (11.97% Laboratory-1; 5.4% Laboratory-2) and bisabolol oxide A (11.97% Laboratory-2) were predominant in *A. arabica*, while eucalyptol (10.97–14.03%), piperitone (9.43–10.43%), and camphor (6.13–12.07%) were prominent in *A. teretifolia*. Location effects confirmed that environmental factors shape metabolite synthesis, with statistically significant differences ($p < 0.05$) showing consistency between instruments.

Heat map analyse (Fig. 1), clarified the inter-species differentiation and location clusters, and the distinct emphasis on the non-polar components (terpenoids) and polar components (oxides, acids) of column polarity highlighted the importance of the analytical method. A literature comparison (Table 1) shows that the results are consistent with general trends in the *Achillea* sp., but that the Malatya locations offer more balanced profiles (lack of ascaridol, richness in *β*-eudesmol). These variations contribute to chemotaxonomic classification and support the antimicrobial, anti-inflammatory, and insecticidal potential of the plants (eucalyptol, camphor, piperitone) (Mohammadhosseini et al., 2017; Polatoğlu et al., 2013; Shiekh et al., 2025; Sökmen et al., 2004; Ünlü et al., 2002).

The multivariate analyses clearly demonstrated that the essential oil compositions of *A. arabica* and *A. teretifolia* form stable and well-defined chemotypic structures. PCA and biplot visualizations confirmed strong species-level discrimination, independent of laboratory conditions, chromatographic column type, or minor analytical variability. Although microenvironmental differences generated measurable intra-specific variation, this secondary variability did not obscure the primary species signatures.

In general, the study emphasizes that *Achillea* sp. are valuable resources for the essential oil industry and pharmaceutical applications, noting that location- and method-based variations can guide sustainable harvesting strategies. Future research could optimize the medicinal and industrial use of these species by examining the biological activities and genetic/environmental interactions of these compounds.

Abbreviations

GC-MS
Gas Chromatography-Mass Spectrometry
RRI
Relative Retention Indices
Std
Standard Deviation
FSC
Fused Silica Capillary
SPME
Solid-Phase Microextraction
SFE
Supercritical Fluid Extraction
ND
Not Detected
Z-score
Standardized Relative Abundance Score
HP-INNOWAX
Polar capillary column (polyethylene glycol)
DB-5MS
Non-polar capillary column (5% phenyl polysilphenylene-siloxane)
IBTAM
Scientific and Technological Research Center (İnönü University)
p-value
Probability value (statistical significance)
C8-C35
Linear alkane series used for retention index calibration

Declarations

Author Contribution

T.K.: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization, Supervision, Project Administration. M.V.: Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Review & Editing. A.P.: Methodology, Validation, Resources, Data Curation, Writing – Review & Editing, Supervision, Funding Acquisition. A.A.H.: Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. A.G.: Investigation, Resources, Writing – Review & Editing.

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Figures

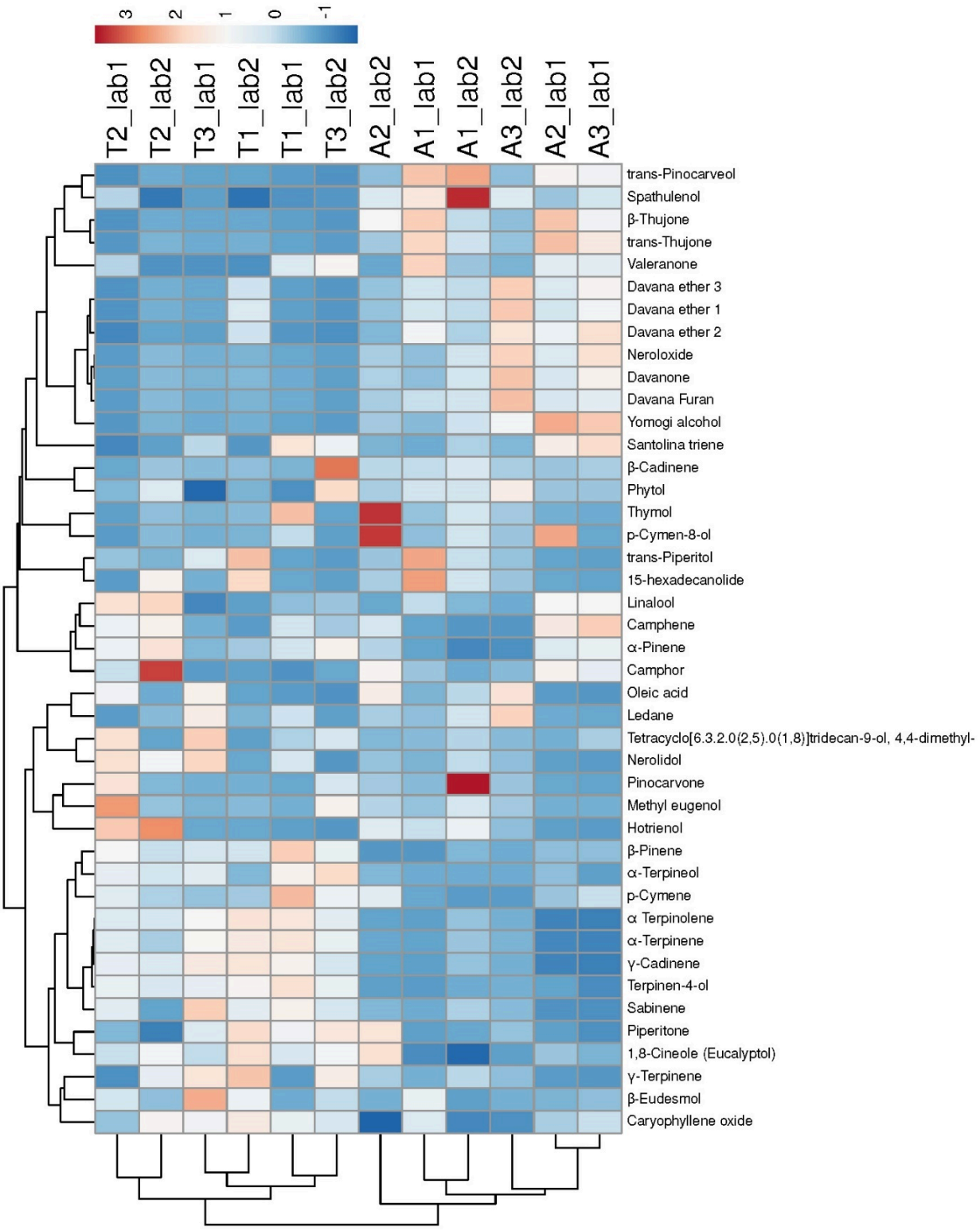

Figure 1

Heat map of essential oil with relative abundance jointly identified in the GC-MS1 (lab1) and GC-MS2 (lab2) instruments. The relative abundance in the heat map plot may implies the color scale which varies from low abundance (blue) to high abundance (red). In this measurement, an increase trend is expressed in red, whilst a decrease is expressed in blue.

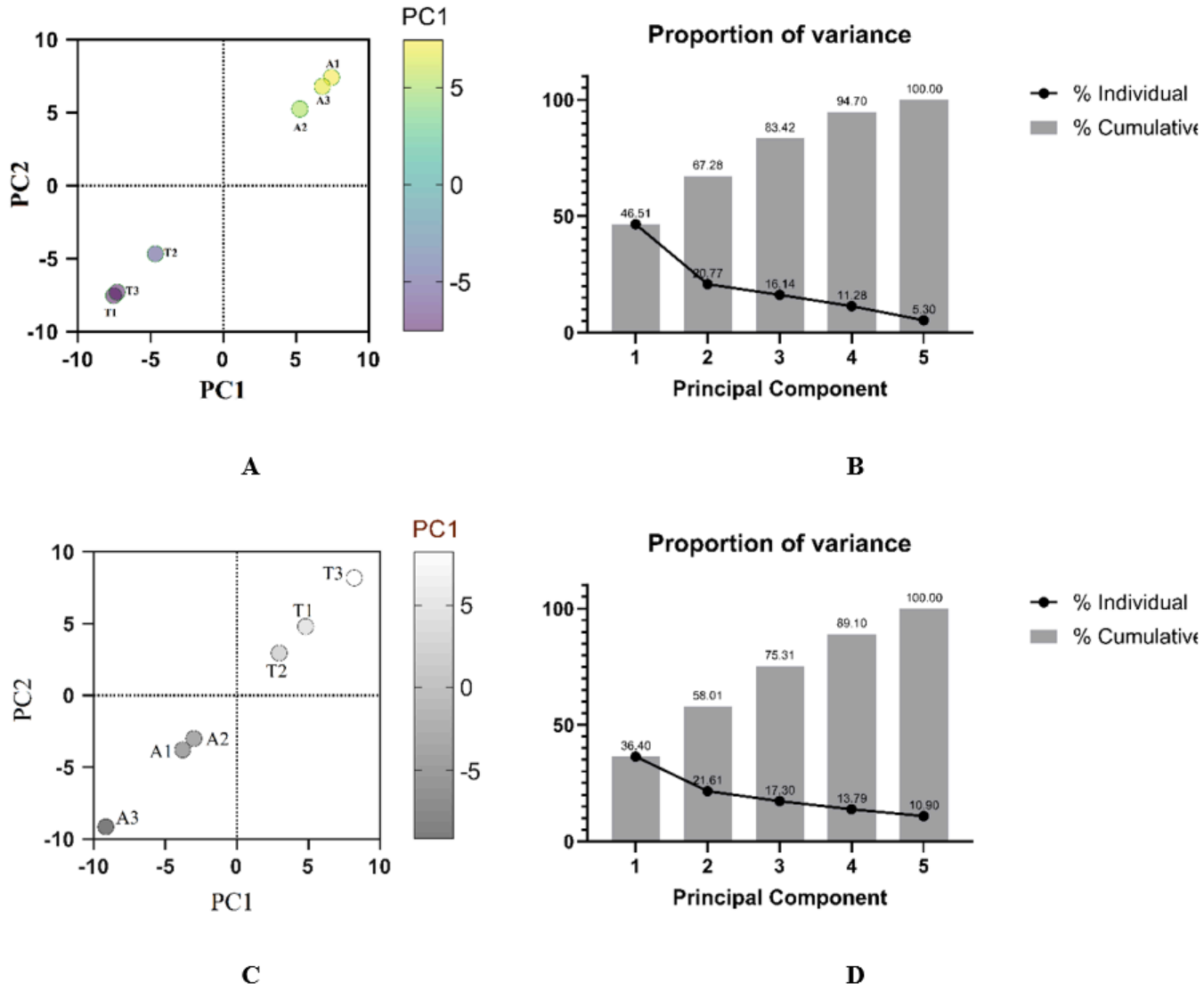

Figure 2

Principal Component Analysis (PCA) of essential oil profiles from A. arabica and A. teretifolia.

A. PCA scores plot from Laboratory-1 showing sample distribution.

B.Scree plot from Laboratory-1 showing proportion of variance explained by each principal component.

C.PCA scores plot from Laboratory-2 showing sample distribution.

D.Scree plot from Laboratory-2 showing proportion of variance explained.

A. arabica; A1 was collected from Pütürge County, A2 from Kale County, and A3 from Hekimhan County. A. teretifolia; T1 was collected from Pütürge County, T2 from Kale County, and T3 from Yeşilyurt County. The color scale shows PC1 values; color usage highlights the distinction.

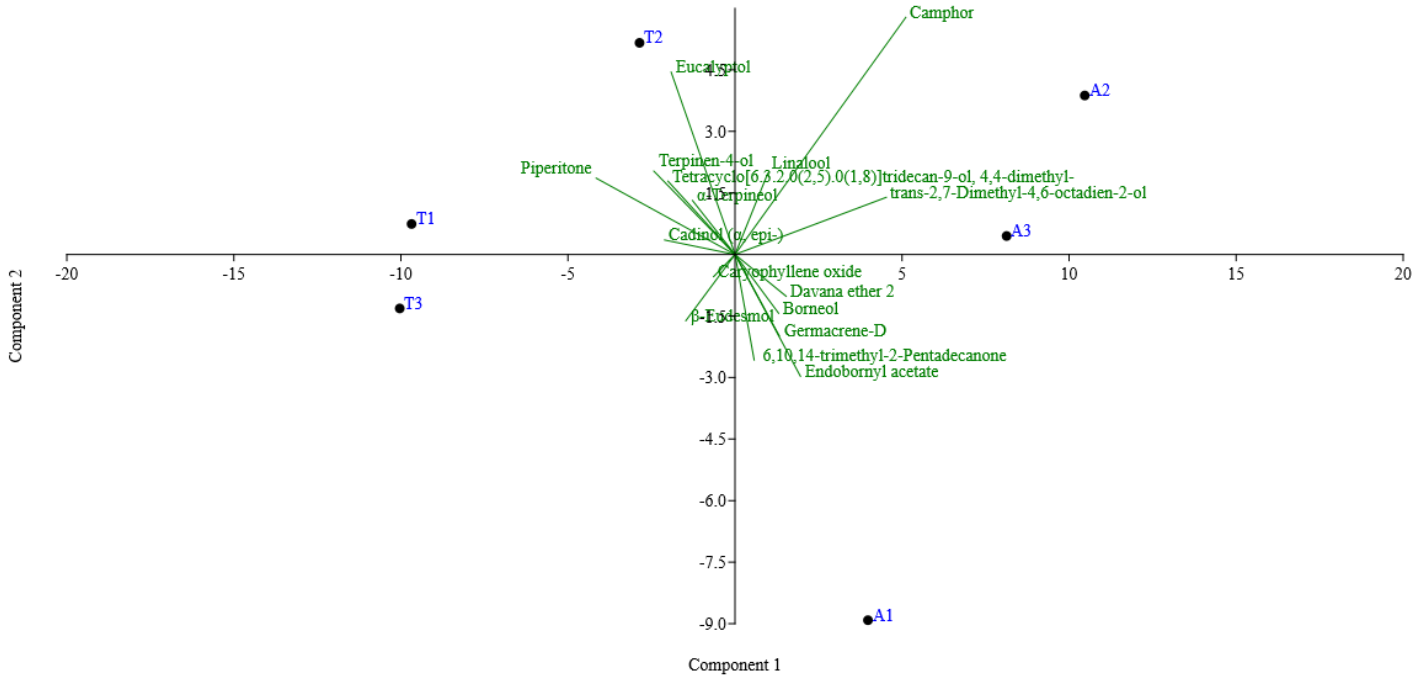

Figure 3

PCA biplot of selected essential oil components from Laboratory-1 (non-polar column)

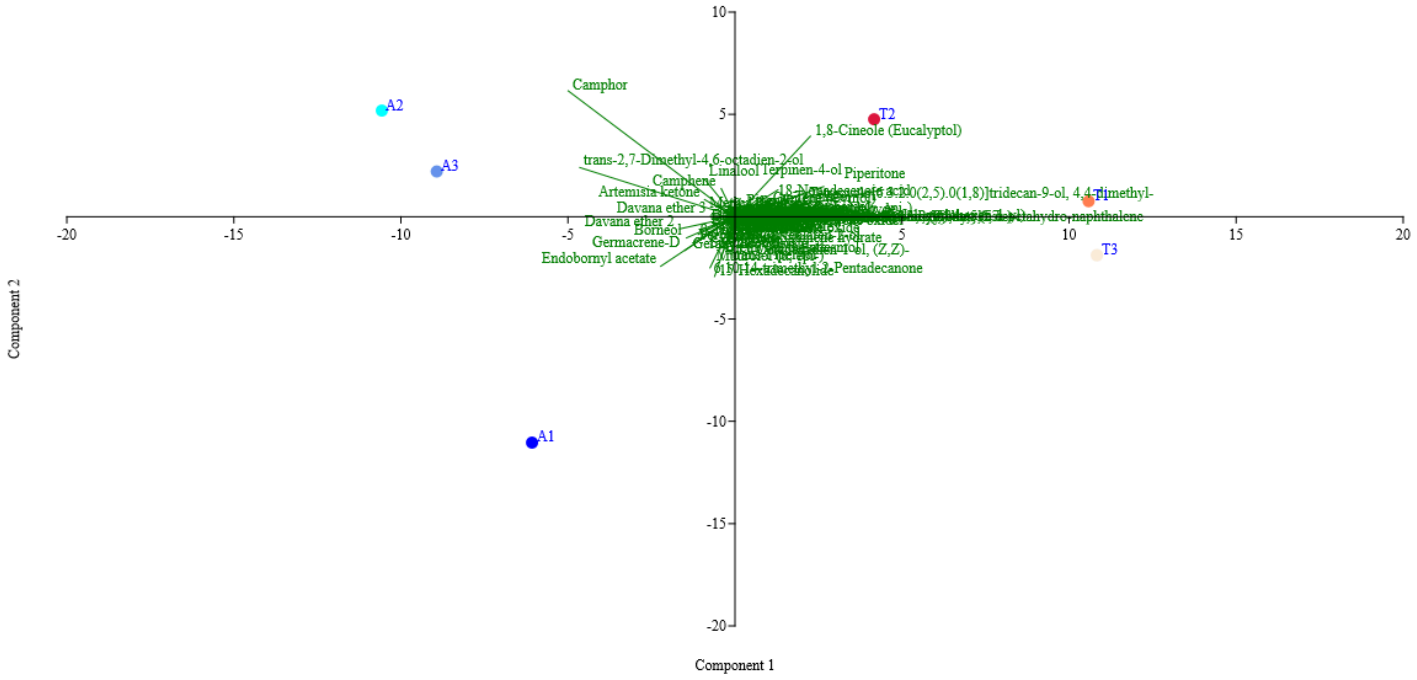

Figure 4

PCA biplot of all detected essential oil components from Laboratory-1 (non-polar column). Loadings and sample vectors (A1–A3, T1–T3) are shown.

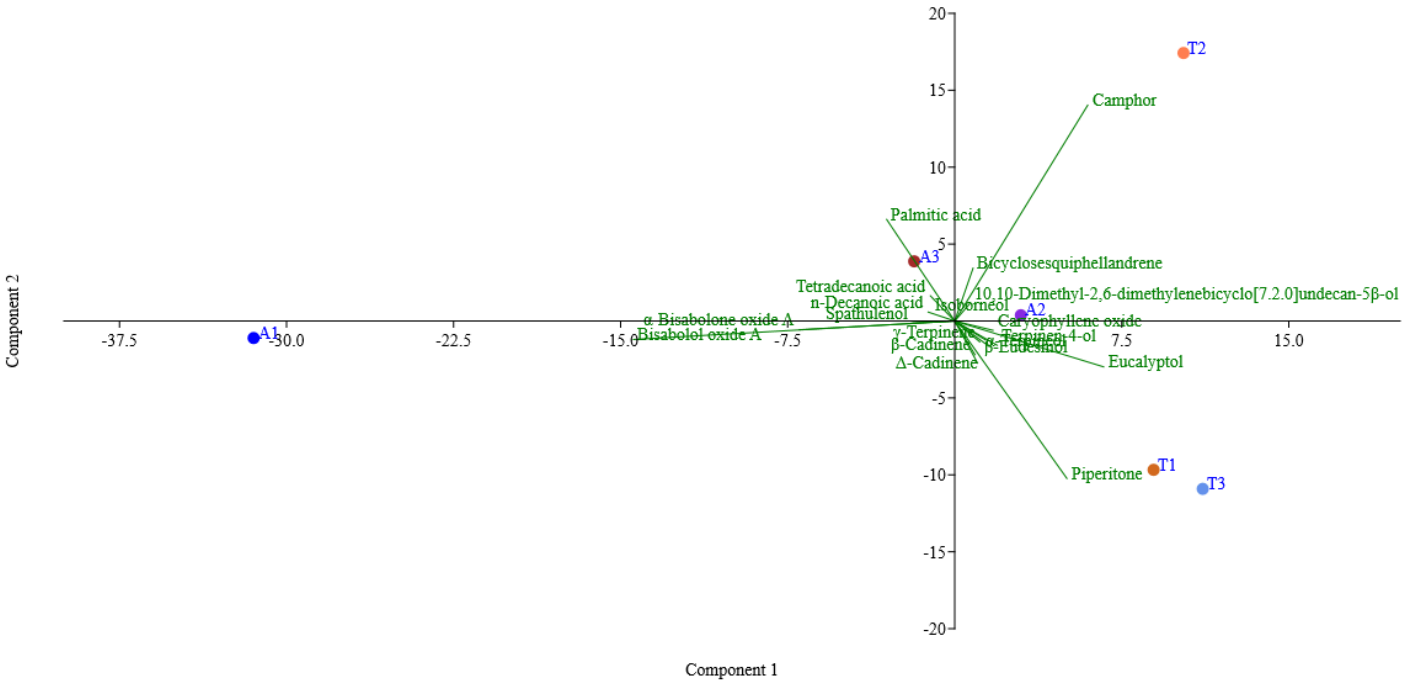

Figure 5

PCA biplot of selected essential oil components from Laboratory-2 (polar column)

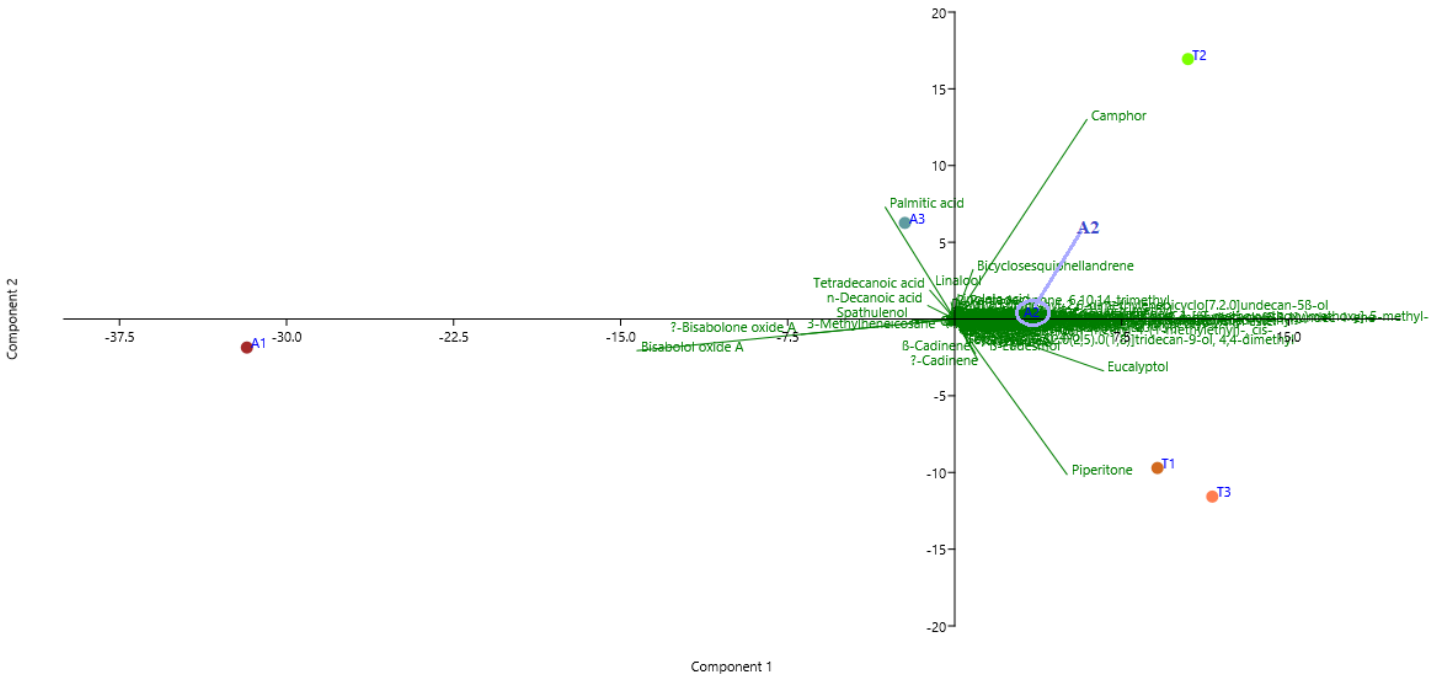

Figure 6

PCA biplot of all detected essential oil components from Laboratory-2 (polar column). Loadings and sample vectors (A1–A3, T1–T3) are shown