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Exploring Phytochemical Diversity and Physiological Attributes of Juniper Species in Iran

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ABSTRACT

Investigating the phytochemical and physiological changes in juniper species is essential for identifying bioactive compounds and enhancing their medicinal uses. A 2022-2023 study evaluated the essential oil content and composition of three juniper species: *Juniperus sabina*, *J. polycarpus*, and *J. communis*. This research was conducted in the Salouk area of North Khorasan, Iran (37° 19.0242' N, 57° 32.7232' E). Herbarium numbers were assigned by the Agricultural Research Center of North Khorasan: *J. communis* (Khsh.CU/*J. communis* 101), *J. polycarpus* (Khsh.CU/*J. polycarpus* 102), and *J. sabina* (Khsh.CU/*J. sabina* 103). Essential oil content per 100 g of dried plant material was 0.5 g for *J. polycarpus*, 1.7 g for *J. sabina*, and 0.54 g for *J. communis* in branches; in fruits, the values were 2.36 g, 3.34 g, and 2.02 g, respectively. *J. sabina* had a significantly higher essential oil content compared to other species, with 29 compounds in its branches and 24 in its fruits identified through Gas Chromatography-Mass Spectrometry. In contrast, *J. polycarpus* contained 19 compounds in branches and 36 in fruits. The fruit extracts showed a significantly higher average percentage of essential oil than branch extracts across all species, with the fruit of *J. communis* containing the highest rate at 98.93%. In the species *J. communis*, the major compounds in the branch were Trans-pinene (15%), α-phellandrene (14.97%), α-pinene (11.28%) and terpinolene (6.66%) and the major compounds in the fruit were α-phellandrene (22.19%), Hexanoic acid (13.50%), β-pinene (8.93%) and sabinene (7.37%). In the species *J. polycarpos*, the major compounds in the branch were benzaldehyde (20.03%), δ-3-carene (5.48%) and Terpinolene (3.71%) and the major compounds in the fruit were Thuja-2,4(10)-diene (43.35%), n-heptanol (6.13%) and 1-octen-3-ol (5.40%). In the species *J. sabina*, the major compounds in the branch were sabinene (12.78%), camphene (12.12%), terpinolene (8.4%) and α-terpinene (6.78%) and the major compounds in the fruit were 1-octen-3-ol (35.27%), α-pinene (7.65%), camphene (5.78%) and Cis-sabinene hydrate (5.15%). This study highlights the potential of ripe fruits in Juniper species as a valuable source of essential oils and emphasizes the critical role of specific genes, particularly the pin gene, in enhancing their biosynthesis.

Keywords: α-Pinene, Bioactive compounds, Essential oil, Phytochemical analysis

INTRODUCTION

Juniper is one of Iran's few valuable coniferous species, belonging to the Cupressaceae family [1]. Its natural habitats cover vast areas of the country, including northern, southern, eastern, western, and even central regions adjacent to Iran's deserts [2]. Juniper and other species within this family hold significant value in botanical, genetic, industrial, landscape, and soil and water conservation. The species exhibits a high tolerance and adaptability to natural and anthropogenic stressors, making it rare to find a tree that has perished due to physiological weakness or pest infestation [3]. These trees possess substantial economic and ecological importance and are considered some of the most vital plant species. Additionally, they demonstrate numerous biological and pharmacological properties and can establish themselves in even the harshest conditions, particularly those involving challenging soil substrates [4]. Of the 60 known juniper species worldwide, only five—*Juniper oblonga*, *J. communis*, *J. sabina*, *J. foetidissima*, and *J. polycarpus*—are native to Iran [2, 4].

The global herbal market predominantly centers on producing and supplying secondary metabolites derived from these plants, which typically possess substantial added value [5]. Key environmental factors influencing the production and accumulation of secondary metabolites include temperature, humidity, light intensity, water availability, mineral content, CO_2 concentrations, and hydroponic conditions [6]. Variations in the chemical composition of essential oils (EO) can be significantly affected by factors such as humidity, soil conditions, temperature, and seasonal changes [7]. Consequently, the primary components of EO exhibit considerable variability depending on the region where the plant is cultivated [8].

Although secondary metabolites in medicinal and aromatic plants are generally influenced by their genotype, the biosynthesis of these compounds is highly dependent on environmental factors [9]. Both biotic and abiotic stresses significantly affect growth parameters, the yield of EO, and their composition [10]. Studies on the EO of juniper have shown that these secondary metabolites possess inhibitory solid effects against various pathogenic fungi, demonstrating antimicrobial properties [11].

J. communis (common juniper) is a monoecious or dioecious tree or shrub belonging to the Cupressaceae family. It features linear, sharp-tipped leaves measuring between 4 and 16 mm, sometimes up to 20 mm in length. This species exhibits both an upright and creeping growth habit, with the upper surface of the leaves displaying a shallow white-silver stripe [12]. *J. sabina* (Savin juniper) is a low-growing, dioecious shrub that reaches a maximum height of 4 m, spreading across the ground in a creeping form. Its branches are slender, with a diameter of about one mm. The leaves differ depending on the plant's maturity: juvenile leaves are needle-like, measuring 5 to 10 mm in diameter, while mature leaves are scale-like, 1 to 2 mm in diameter, dark green in color, and bear small, round, black fruits [13]. *J.*

polycarpos (Persian juniper) is a dioecious, medium-sized, conical tree with scaly, ovate-triangular leaves arranged in four rows along the branches. The fruit is spherical, dark blue to nearly black, covered with a white powdery coating, and consists of four scales and 4 to 5 seeds. The EO from this species exhibits potent antifungal activity against plant pathogenic fungi [14].

The evaluation and comparison of EO composition across different species of plants, such as juniper, is crucial due to genetic diversity and the influence of environmental factors [12]. These analyses offer valuable insights into the variations in chemical profiles and medicinal properties between species, facilitating the identification of those with the greatest industrial and economic potential. Moreover, such studies play a pivotal role in biodiversity conservation, advancing scientific understanding, supporting the development of new pharmaceutical and cosmetic products, informing conservation strategies and optimizing commercial cultivation practices [15]. Radoukova et al. [16] found that the EO content and composition exhibited significant variability among different juniper species and even within the same species, influenced by plant genus and geographical location. In the *J. communis* EO sourced from Slovakia and Serbia, α-Pinene was identified as the predominant compound, comprising 25.1–27.0% and 21.8–22.2%, respectively. In contrast, Bulgaria's primary constituent in the *J. communis* EO was sabinene, accounting for 19.8–27.9%. Consequently, the present study was conducted to assess the EO profile and phytochemical variations in three significant juniper species (*J. sabina*, *J. polycarpus*, and *J. communis*) within the North Khorasan region of Iran.

MATERIALS AND METHODS

Collection of Juniper from Natural Habitats

The study was conducted in two phases: field collection from natural habitats and subsequent laboratory analyses between 2022 and 2023. We identified and collected three juniper species—*J. sabina*, *J. polycarpus*, and *J. communis*—from the Salouk region, located south of Bojnord in North Khorasan, Iran (see Fig. 1). After identification, herbarium numbers were assigned by the Agricultural Research Center of North Khorasan: *J. communis* (Khsh.CU/J. communis 101), *J. polycarpus* (Khsh.CU/*J. polycarpus* 102), and *J. sabina* (Khsh.CU/J. sabina 103). This area is defined by geographical coordinates ranging from latitude 37°15' N to 37°07' N and longitude 57°17' E to 57°03' E. The Salouk region in North Khorasan exhibits a semi-arid climate characterized by hot, dry summers with temperatures reaching 22.82 °C and cold winters dropping to around -5 to 5 °C. The area receives limited annual precipitation of approximately 1.00 mm per day, primarily as rain and snow during the autumn and winter, totaling around 200-400 mm annually. The vegetation predominantly consists of drought-resistant species, including juniper trees, thriving under relative humidity levels ranging from 32.07% to 78.25%. The region experiences approximately 60-100 frost days per year and has a growing season extending from April to October, with prevailing northwest winds (Table 1). Juniper populations in North Khorasan typically thrive in calcareous soils and rocky terrains, primarily in mountainous regions at elevations exceeding 2000 MASL, with some occurrences documented at altitudes above 3000 MASL, particularly in areas such as Salouk. To ensure accurate species identification, specimens were verified by a botanist.

Table 1 Climatic parameters of the region for Juniper sample collection (2018-2024)

Climatic parameter	Value
Minimum temperature (°C)	9.67
Maximum temperature (°C)	22.82
Average temperature (°C)	16.08
Minimum relative humidity (%)	32.07
Maximum relative humidity (%)	78.25
Average relative humidity (%)	54.32
Average daily precipitation (mm)	1.00
Wind speed ($m.s^{-1}$)	8.90

Soil Sampling

To evaluate the physicochemical properties of the soil and their correlation with the quantity and quality of the studied plant, soil samples were collected from beneath the canopy at a depth of 30 cm at three points along a 100 m transect in each habitat. The samples were air-dried, ground in a mortar, and sieved through a 2 mm mesh. Key soil parameters such as nitrogen, phosphorus, potassium, electrical conductivity, lime content, organic carbon, soil texture, and micronutrients were then analyzed (Table 2).

Table 2 Physicochemical properties of soils from the habitats of different Juniper species.

Parameters	Symptoms	Unit	Test result Desired limit	Depth 0 - 30 cm
Acidity	pH	-	6.5-7	7.7
Electrical conductivity	EC	$Ms.cm^{-1}$	<3	1.3
Soil saturation percentage	SP	%	35-40	41
Neutralizing materials (lime)	TNV	%	<10	2
Organic carbon	O.C	%	1.5-2	3.8
Nitrogen	N	%	0.1-0.2	0.34
Absorbable phosphorus	$P_{A.V}$	$mg.kg^{-1}$	10-12	2
Absorbable potassium	$K_{A.V}$	ppm	300-350	962
Soil texture				
Sand	Sand	%	40	36
Silt	Silt	%	35	60
Clay	Clay	%	25	4
Soil texture class	-	-	Loam	Silt loam

Micronutrients				
Iron	Fe	$mg.kg^{-1}$	5-20	-
Copper	Cu	$mg.kg^{-1}$	0.5-2	-
Manganese	Mn	$mg.kg^{-1}$	5-30	-
Boron	B	$mg.kg^{-1}$	22-60	-
Zinc	Zn	$mg.kg^{-1}$	0.5-6	-

Essential oil Extraction

Fresh one-year-old green branches from trees of uniform age across the three species and the fruit (cones or galbuli) from each species were collected and air-dried in a well-ventilated, shaded area. After grinding, the EO were extracted via hydrodistillation using a Clevenger apparatus for 2 to 5 h. The extracted oils were dehydrated with sodium sulfate, stored in dark glass vials at 4 °C, and protected from light to preserve their composition until further analysis [11, 12].

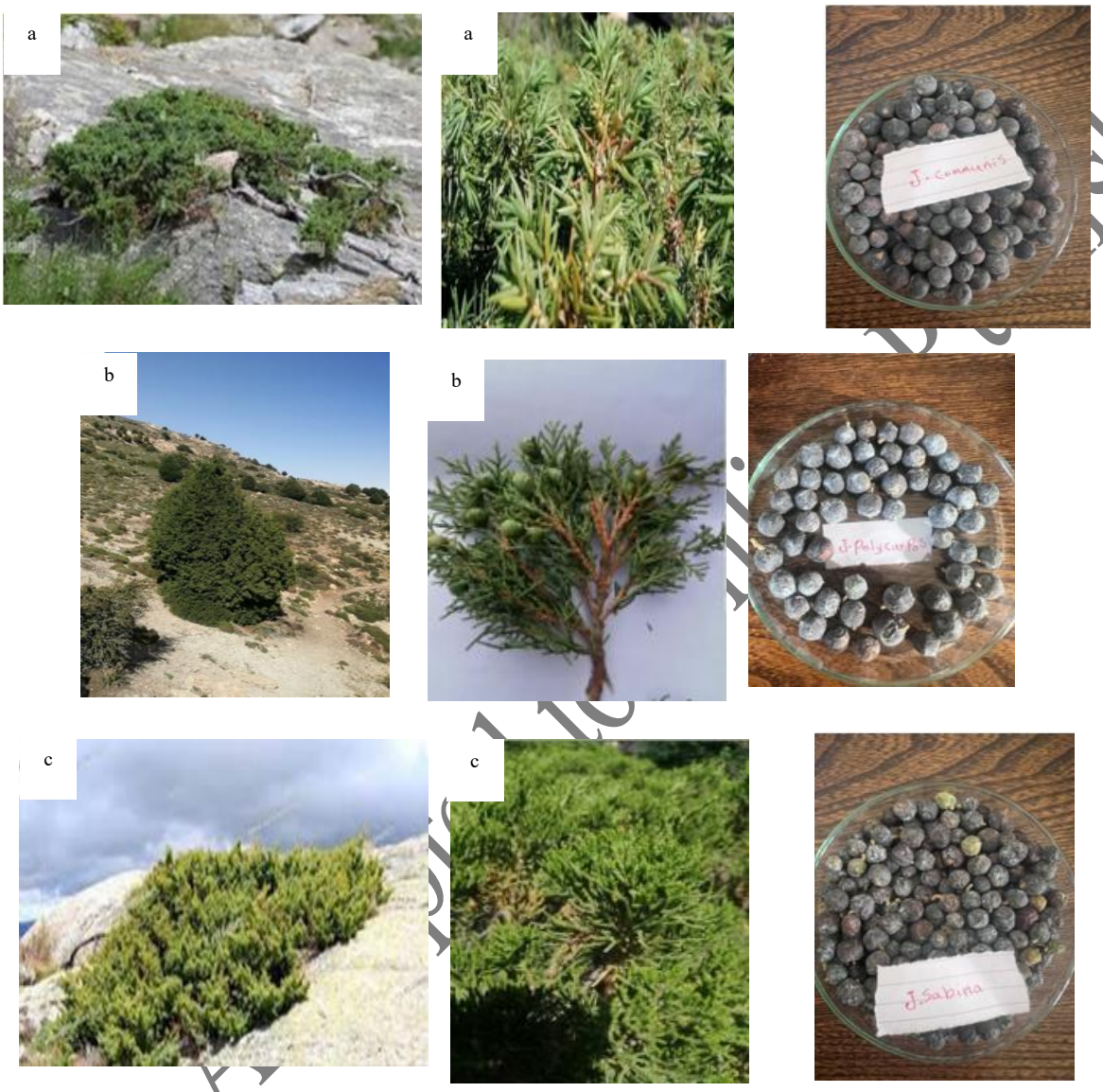

Fig. 1 Samples of trees, branches, and fruits from three juniper species: *J. communis* (A), *J. polycarpos* (B), and *J. sabina* (C) in the North Khorasan region of Iran

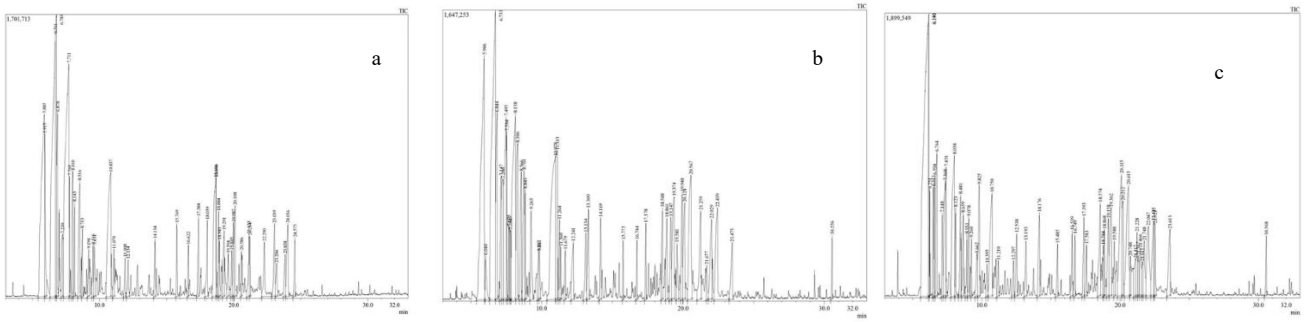

Fig. 2 GC-MS chromatogram of the essential oil analysis from the branches of three juniper species: *J. communis* (A), *J. sabina* (B), *J. polycarpus* (C)

Device Conditions

The EO obtained from the plant was analyzed using Gas Chromatography-Mass Spectrometry (GC-MS) to identify its chemical components. The mass spectra of the constituents were obtained, and the Kovats index (KI) for each compound was calculated using a temperature-programmed GC-MS system. The components were identified by comparing their retention times and KI with those of standard compounds and by matching their mass spectra [12]. The GC-MS analysis was performed using a Shimadzu-QP2010SE gas chromatograph with an Rtx-5MS column (30 m length, 0.25 mm internal diameter, and 0.25 µm film thickness). The column temperature program started at 45 °C with a 1-min hold, followed by a ramp of 5 °C/min until reaching 250 °C, where it was held for an additional 5 min. Helium was used as the carrier gas at a 0.9 mL/min flow rate, and the mass spectrometer operated at an ionization energy of 70 eV. To confirm the identification of the compounds, a chromatogram of normal paraffin (C5-C30) was generated under the same conditions, allowing for the calculation of the KI for each component based on their retention times [12]. The chromatogram samples obtained from the analysis of the branches of the three juniper species are presented in Fig. 2.

$$KI = 100n + 100\left(\frac{Trx - Trn}{((Trn+1) - Trn}\right) \quad (1)$$

Statistical Analysis

The data collected were analyzed using SAS software version 9.2 following a normality test (Kolmogorov-Smirnov). Simple correlations between traits were calculated using Excel 2018 and Minitab version 18.

RESULTS

Essential Oil Content

The EO content extracted from 100 g of dried plant material in one liter of distilled water was evaluated for three species of juniper: *J. polycarpus*, *J. sabina*, and *J. communis*. The results revealed that the EO yields for the branches of these species were relatively low, with *J. polycarpus* yielding 0.5 g, *J. sabina* producing 1.7 g, and *J. communis* offering 0.54 g 100 g of dried material.

In stark contrast, the EO content in the ripe fruits of the same species was significantly higher, with *J. polycarpus* yielding 2.36 g, *J. sabina* providing 3.34 g, and *J. communis* offering 2.02 g. Notably, *J. sabina* exhibited a statistically significant superiority in EO content compared to the other two species, indicating its potential as a particularly rich source of EO.

Furthermore, a comparison of the two plant parts revealed a consistent trend: the EO content in the fruits surpassed that of the branches for all three species examined. This finding emphasizes the fruits' role as a more advantageous source of EO within these juniper species. The enhanced EO content in the fruits not only highlights their commercial potential but also suggests that harvesting ripe fruits may be a more effective strategy for obtaining EO compared to utilizing the branches. Such insights are crucial for both ecological and economic considerations in the utilization of these juniper species for EO production (Fig. 3).

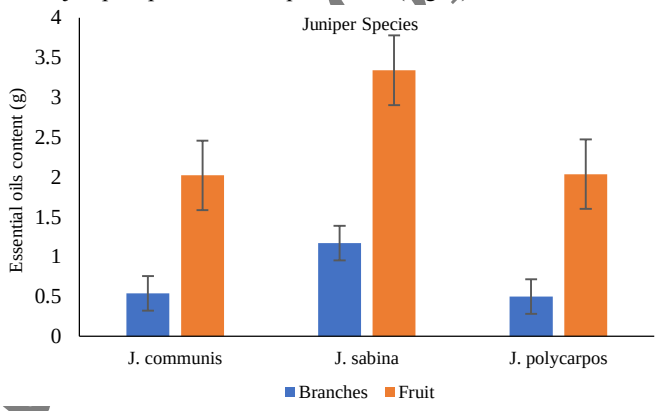

Fig. 3 Percentage content of essential oil in three Juniper species for fruits and branches

Analysis of Essential Oil

In this study, a comprehensive analysis of EO was conducted using GC-MS on three distinct species of juniper: *J. communis*, *J. sabina*, and *J. polycarpos*. A total of 82 compounds were identified from both the branches and fruits of these species, highlighting the complexity and diversity of the EO profiles.

The distribution of identified compounds revealed notable differences between the plant parts. This substantial difference indicates a pronounced variation in EO yield and composition between the different parts of these juniper species, suggesting that fruits may be a more lucrative source for EO extraction (Table 3).

In the species *J. communis*, the major compounds in the branch were Trans-pinene (15%), α-phellandrene (14.97%), α-pinene (11.28%) and terpinolene (6.66%) and the major compounds in the fruit were α-phellandrene (22.19%), Hexanoic acid (13.50%), β-pinene (8.93%) and sabinene (7.37%). In the species *J. polycarpos*, the major compounds in the branch were benzaldehyde (20.03%), δ-3-carene (5.48%) and Terpinolene (3.71%) and the major compounds in the fruit were Thuja-2,4(10)-diene (43.35%), n-heptanol (6.13%) and 1-octen-3-ol (5.40%). In the species *J. sabina*, the major compounds in the branch were sabinene (12.78%), camphene (12.12%), terpinolene (8.4%) and α-terpinene (6.78%) and the major compounds in the fruit were 1-octen-3-ol (35.27%), α-pinene (7.65%), camphene (5.78%) and Cis-sabinene hydrate (5.15%). respectively (Table 3).

Table 3 Identified compounds of essential oil from the fruits and branches of three Juniper species in the North Khorasan region

No.	Compounds name	R. time	R. index	*J. communis*		*J. polycarpos*		*J. sabina*	
				Branches	Fruits	Branches	Fruits	Branches	Fruits
1	Tricyclene	5.51	921		0.75				
2	α- thujene	5.70	924		4.28				
3	α- pinene	5.85	932	11.28	3.00				7.65
4	α- fenchene	5.90	945	1.97	4.23				3.60
5	camphene	5.92	946					10.12	5.78
6	benzaldehyde	6.14	952			20.03			
7	Thuja-2,4(10)-diene	6.22	953			3.00	43.35		
8	n-heptanol	6.30	952			0.68	6.13		
9	Isoamyl propionate	6.35	960				4.33		
10	verbenene	6.39	961			1.51	1.00		
11	Hexanoic acid	6.45	967		13.50	1.28	1.98	0.75	
12	Trans-pinene	6.50	969	15.00	1.67		2.38		
13	sabinene	6.73	969	4.44	7.37	2.91		12.78	
14	1-octen-3-ol	6.81	974	3.23			5.40		35.27
15	β- pinene	6.86	974		8.93			2.82	
16	Trans-isolimonene	7.20	980	1.34		1.27		1.96	4.23
17	Cis-pinene	7.28	982					2.42	1.38
18	Myrcene	7.36	988			2.88	2.86		0.86
19	3-octanol	7.43	988			1.54		4.75	3.63
20	Ethyl hexanoate	7.53	997					1.11	
21	α- phellandrene	7.67	1002	14.97	22.19			0.72	1.96
22	p-menta-1 (7), 8-diene	7.73	1003	0.99				0.73	
23	Dihydroxy cis-linalool oxide	7.79	1006				1.43	0.50	2.46
24	δ-3- carene	8.20	1008	2.40	2.16	5.48			
25	α- terpinene	8.30	1014	0.98	1.37	0.75		6.78	1.61
26	p-cymene	8.40	1020	2.27		1.80	4.15	3.34	2.81
27	Methyl heptanoate	8.56	1021		3.92	1.22		1.93	2.10
28	limonene	8.69	1024	0.79	0.88				0.82
29	1,8-cineole	8.76	1026		0.96			2.47	
30	(z) - β--ocimene	8.84	1032			0.66		0.94	
31	(E) - β--ocimene	9.10	1044			1.12			
32	Isobutyl angelate	9.19	1045	0.80		0.58		1.52	
33	bergamal	9.35	1051	2.27					
34	γ- terpinene	9.63	1054	1.07		0.95	1.11	0.76	
35	Artemisia ketone	9.82	1056			2.57		0.51	
36	Cis-sabinene hydrate	10.39	1065			0.59	1.32		5.15
37	terpinolene	10.75	1086	6.66	5.44	3.71		8.04	
38	linalool	11.10	1095	0.88	0.83	0.54		3.38	
39	Trans-sabinene hydrate	11.26	1098					0.91	
40	Cis-thujone	11.36	1101					0.50	
41	Isopentyl isovalerate	11.67	1102	0.67				0.61	
42	Trans - thujone	12.20	1112	0.73		0.54		1.13	
43	α-campholenal	12.53	1122			1.14		1.16	0.83
44	camphor	13.18	1141			1.06		1.20	1.12
45	borneol	14.13	1165	0.81		1.62	1.20	1.07	
46	α- terpineol	15.47	1186	1.04		0.74	2.47	0.48	1.14
47	Verbenone	16.53	1204	0.65		0.79	0.99		
48	Cis-sabinene hydrate acetate	16.74	1219			0.74	1.45	0.52	1.50
49	Hexyl isovalerate	17.37	1241	1.21	1.50	1.19		0.71	2.43
50	Isoamyl hexanoate	17.57	1246			0.63			0.71
51	Cis-myrtanol	18.10	1250	1.43	2.77		1.91		1.28
52	Trans -sabinene acetate	18.54	1253	5.02		2.24		1.10	2.65
53	Linalool acetate	18.77	1254		8.93	0.63			
54	Trans-myrtanol	18.86	1258	1.32		0.76		1.23	
55	Isopropyl phenylacetate	18.89	1267	0.65	1.28				
56	α- terpinene-7-al	19.20	1283	1.43	0.98	1.63	0.96	1.38	0.74
57	Bornyl acetate	19.36	1284			2.67		2.55	
58	Trans-sabinyl acetate	19.58	1289	0.73		0.84		0.89	
59	γ- terpinene-7-al	19.84	1290	0.67			1.63		0.96
60	Methyl acetate	19.94	1294	1.14				1.65	
61	Geranyl formate	20.20	1298	1.93	1.99				
62	Terpinene-4-ol aceate	20.35	1299			4.75	4.75	1.99	4.65
63	n-tridecane	20.45	1300		1.05	1.92			1.35
64	Cis- pinocarvyl acetate	20.55	1311		1.05	4.65			
65	δ- terpinyl acetate	20.65	1316	0.80		0.53		3.83	

66	Myrtenyl acetate	21.20	1324	1.08	1.02				
67	p-mentha-1,4-dien-7-ol	21.35	1325	0.83	1.30		1.91		
68	Isobutyl benzoate	21.46	1327		0.68				
69	Cis-piperitol acetate	21.55	1332		1.32				
70	δ- elemene	21.61	1335		0.58				
71	Trans- carvyl acetate	21.76	1339		1.50		0.47		
72	Verbenol acetate	22.22	1340		2.95		1.89		
73	Benzyl butanoate	22.29	1343	1.41	1.90				
74	α- tepinyl acetate	22.43	1346		0.74		2.85		
75	α- cubebene	22.52	1345	1.70	1.20				
76	α- copaene	23.20	1374	0.71					0.69
77	Hexyl hexanoate	23.38	1382	0.83	0.72	1.78			
78	β- bourbonene	24.24	1384	1.76					
79	β- elemene	24.57	1389	1.02					
80	α- muurolene	29.64	1500			1.18			
81	γ- cadinene	29.73	1513			1.43			
82	α- cadinene	30.55	1537		0.72	4.76	0.57		

DISCUSSION

The innovation of this research involves a comparative analysis of the yield and essential oil composition between the branches and ripe fruits of three juniper species (*J. sabina*, *J. polycarpus* and *J. communis*) from the Saluk region of Iran, which revealed significantly higher essential oil content and distinct chemical profiles in the fruits, especially the abundance of 1-octen-3-ol in *J. sabina* fruits and α-phellandrene in *J. communis* fruits. The experimental results show that the EO content in the fruits of all three juniper species is higher than in the branches, emphasizing the importance of ripe fruits as a superior source of EO. Given the climatic conditions of the Saluk region - characterized by hot and dry summers, cold winters, low relative humidity and limited rainfall - the influence of these parameters on the changes in EO content requires further investigation. High temperature and dry conditions may increase the production of EOs in plants, while low relative humidity can negatively affect the quality and concentration of these oils. Furthermore, limited rainfall during autumn and winter may facilitate the accumulation of nutrients in fruits and increase the content of EOs. This relationship between climatic factors and the changes in EOs in fruits and branches of different Juniper species highlights the need for more detailed investigations into these effects to optimize EO production and medicinal applications. Furthermore, previous studies have reported significant effects of climatic parameters on the content of plant metabolites, as evidenced in research on saffron [17] and stevia [18].

Soil physicochemical properties influence the variation of metabolites in different juniper species. This study investigated the EO content and its compounds in three juniper species (*J. sabina*, *J. polycarpus* and *J. communis*) and showed that EO content was highest in fruits, especially in *J. sabina*. Factors such as pH, nutrient availability and soil texture significantly affect the production of secondary metabolites, especially the presence of nitrogen and micronutrients such as zinc, which play an important role in the synthesis of metabolites. In this context, researchers have emphasized that soil physicochemical properties, especially potassium and phosphorus levels, significantly affect EO content and synthesis [19].

Analysis showed that the essential oil of J. communis branches contained a total of 40 identified compounds, accounting for 91.97% of the oil, with the major compounds being trans-pinene (15%), α-phellandrene (14.97%), α-pinene (11.28%) and terpinolene (6.66%). In contrast, 24 compounds were identified in the fruit, including α-phellandrene (22.19%), hexanoic acid (13.50%), β-pinene (8.93%) and sabinene (7.37%). Similarly, Salamon et al. [20] and Zouave et al. [21] reported sabinene as the main compound in the essential oil of *J. sabina*. Kazemi *et al.* [22] identified sabinene (13.14%) as the main component of the essential oil of *J. communis*. Other dominant compounds in this species include α-pinene, limonene, terpinen-4-ol and germacrene D. Melero-Bravo et al. [23] evaluated the essential oil composition of *J. communis* branches and identified the main compounds as α-pinene (12.3–56.4%), β-flandrene (10.0–29.8%) and limonene (3.4–25.7%). Furthermore, Ghorbanzadeh et al. [12] showed that the compounds identified in *J. communis* include α-pinene, β-pinene, myrcene, sabinene and limonene.

The study by Fajr *et al*. [24] also showed that in both branches and fruits of *J. communis*, sabinene, α-pinene, limonene, terpinen-4-ol and germacrene D were the most abundant compounds, with sabinene being the most abundant. The present study identified α-phellandrene as a major compound in *J. communis* (branches and fruits).

Phellandrenes are used in perfumes due to their pleasant aromas. α-Phellandrene can form dangerous peroxides with air at high temperatures. The DNA moiety in X can be used for diastereoselective cyclization of trans to isopropyl (https://www.sciencedirect.com). Phellandrene is a colorless to light yellow oily liquid. It has a black pepper odor. The flash point is 49 °C. Boiling point (2133 Pascals) (http://www.thegoodscentscompany.com).

In contrast, the essential oil of *J. sabina* fruits contained 28 identified compounds (92.77%), the major compounds being 1-octen-3-ol (35.27%), α-pinene (7.65%), camphene (5.78%), and Cis-sabinene hydrate (5.15%). In this regard, Ghorbanzadeh [12] identified 25 compounds in *J. sabina*, with sabinene (40.1%) and α-pinene (5.8%) as the main components. In addition, Zhelyazhkov *et al.* [25] identified sabinene, terpinen-4-ol, and α-cadinol as the main components of *J. sabina* essential oil. For the essential oil of *J. polycarpos* fruits, 24 compounds (90.16%) were identified, with the major compounds being Thuja-2,4(10)-diene (43.35%), n-heptanol (6.13%) and 1-octen-3-ol (5.40%). In the essential oil of *J. polycarpos* branches, 55 compounds (87.26%) were identified, with the major compounds in the branches being benzaldehyde (20.03%), δ-3-carene (5.48%) and Terpinolene (3.71%) as the dominant components.

Furthermore, the results showed that the essential oil of the fruits of each species (except *J. polycarpos*) contained a lower number of compounds but a higher average percentage of those compounds compared to the essential oil of the corresponding branches. The highest amount of compounds was observed in the fruits of *J. sabina*. The findings of Vaičiulytė and Ložienė [27] also show that in *J. communis*, the essential oil concentration and intraspecific diversity of compounds are higher in the cones (fruits) than in the leaves. Chemical analysis

of thyme essential oil, as reported by Mehrabi *et al.* [28], revealed the presence of 23 compounds, which constitute 83.68% of the total essential oil composition. Thymol was identified as the main component, which constitutes 25.30% of the essential oil. In their study on essential oils and antibacterial activity, Alamuti *et al.* [29] found that Shirazi thyme essential oil showed the highest efficacy against the tested bacteria, while cumin and oregano essential oils showed semi-sensitive antibacterial properties. According to Mahmoudi *et al.* [30], the essential oil of Ferula Sharifi is mainly composed of monoterpene hydrocarbons (43.9%), with β-pinene (21.7%), α-pinene (15.9%), and sabinene (5.7%) being the most abundant compounds in this chemical class.

CONCLUSION

GC-MS analysis of different Juniper species revealed significant qualitative and quantitative variations in their EO profiles. Notably, the branch oil of *J. communis* was characterized by a specific dominant composition, distinct from the dominant composition identified in its fruit oil. Similarly, EO extracted from the branches and fruits of *J. sabina* and *J. polycarpus* showed unique dominant compositions. Interestingly, *J. polycarpus* showed particularly high levels of benzaldehyde and Thuja-2,4(10)-diene. Comparative analysis revealed that fruit-derived EO generally contained a lower number of compounds but exhibited a higher average percentage of identified compounds, particularly evident in *J. communis*. This observation suggests that juniper species with simpler but more concentrated EO compounds, such as J. communis, have significant potential for commercial and medicinal applications, and emphasizes the significant value of juniper plants and their diverse oil compositions for future breeding and breeding programs aimed at enhancing specific oil profiles.

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