

RESEARCH IN COMPONENT COMPOSITION OF ESSENTIAL OILS FROM VARIOUS ORGANS OF *SILPHIUM PERFOLIATUM* L.

Liubomyr Lytvynets, Andriy Grytsyk, Ivan Bilai, Oleh Koshovyi, Ain Raal

Silphium perfoliatum L. (cup plant) is a perennial member of the Asteraceae family indigenous to eastern North America. Its phytochemical profile and biological properties have not yet been comprehensively characterised, and the species is not included in official medical practice. Nevertheless, ethnobotanical records indicate that Indigenous communities of North America traditionally used this plant to alleviate conditions such as neuralgia, respiratory ailments, and rheumatic disorders.

The aim. The aim of this study was to conduct a comprehensive analysis of the qualitative and quantitative composition of essential oils isolated from different organs of *S. perfoliatum* L. to identify organ-dependent variations and expand current knowledge on the phytochemical profile of this species.

Materials and methods. The plant materials of *S. perfoliatum* used in this study were collected in Ivano-Frankivsk, Ukraine. Hydrodistillates obtained from dried various organs of *S. perfoliatum* L. according to the methods of the European Pharmacopoeia were analyzed using gas chromatography coupled with mass spectrometric detection (GC–MS) using an Agilent 6890/5973 GC–MS system operated with ChemStation software for mass-selective detectors (MSD). Agilent HP-5MSI capillary column (30 m × 0.25 mm i.d., film thickness 0.25 µm) were used.

Research results. The yields of essential oils (EOs) in *S. perfoliatum* L. organs ranged from 2.66 to 5.46 mL/kg. In total, 84 volatile compounds were identified in the raw materials, including monoterpenoids, sesquiterpenes, diterpenes, aldehydes, and other aroma compounds. Sesquiterpenes were the dominant class in all samples (60.44–77.53%). Caryophyllene oxide, germacrene-type alcohols, and caryophyllene prevailed in the aerial parts, whereas root distillates were characterised by silphiperfol derivatives such as silphiperfol-5-ene and presilphiperfol-7-ene. Monoterpenes were most abundant in flowers (23.60%), with α -pinene and camphene as key constituents, while roots contained negligible amounts. Diterpenes, mainly phytol, were detected predominantly in leaves, highlighting organ-specific differences in volatile biosynthesis. A comparative analysis of leaf essential oils collected in 2023 and 2024 demonstrated qualitative stability with quantitative variation. Sesquiterpenes remained dominant in both years (67.19% in 2023; 60.51% in 2024). Caryophyllene oxide and germacrene-type alcohols were major constituents in both samples, though phytol content increased markedly in 2024 (16.54% vs 5.46%). In contrast, 2023 samples showed higher levels of monoterpenes (7.97% vs 5.88%) and aldehydes (7.72% vs 4.36%), indicating seasonal shifts in volatile composition.

Conclusions. This research elucidates the volatile profiles of *S. perfoliatum* from different organs and harvest years, demonstrating clear organ-related and interannual variability. The content of volatile fractions varied from 2.66 to 5.46 mL/kg, depending on the plant organs. A total of 84 volatile compounds were identified, with sesquiterpenes representing the dominant class in all samples (60.44–77.53%). Aerial parts were enriched in oxygenated sesquiterpenes such as caryophyllene oxide and germacrene-derived alcohols, whereas roots showed a distinct chemotype dominated by silphiperfol-type hydrocarbons. Monoterpenes were most abundant in the flowers (23.60%), with α -pinene, camphene, and oxygenated monoterpenes contributing substantially to the volatile profile, while their content in roots was negligible. Overall, these results broaden current understanding of the phytochemical diversity of *S. perfoliatum* and support further investigation of its essential oils for potential biological and applied uses

Keywords: *Silphium perfoliatum* L., Asteraceae, essential oil, component composition, GC/MS

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1. Introduction

Silphium perfoliatum L. (cup plant) is a perennial plant species belonging to the family Asteraceae, native to the eastern coastal regions of North America. The plant is characterised by massive, erect, quadrangular stems, glabrous or less frequently pubescent, often branched, reaching a height of 70–300 cm. The leaves are of two types: basal leaves, which are temporary, and

cauline leaves, which are opposite or, more rarely, arranged in irregular whorls; they are lanceolate to ovate in shape. The inflorescences are capitula bearing yellow florets [1, 2].

In the wild, *S. perfoliatum* grows in the prairies of North America, particularly along the northeastern coastal areas of the United States and Canada [3]. The species was introduced to Europe in the 19th century as

an ornamental plant. Since the early 2000s, it has been cultivated as a high-energy crop due to its high biomass yield and elevated amino acid content [4, 5].

The chemical composition and pharmacological activity of *S. perfoliatum* remain insufficiently studied. Among the compounds identified to date, phenolic acids, namely caffeic, *p*-coumaric, ferulic, protocatechuic, vanillic, and chlorogenic acids, have been isolated and characterised from extracts of roots and rhizomes, leaves, and inflorescences [6]. Terpenoids have been detected at concentrations ranging from 0.19% to 0.41%, depending on the plant organ. The dominant constituents of essential oils obtained from the aerial parts are pinene (16.8–20.9%) and caryophyllene oxide (8.5–34.7%). In contrast, the roots are rich in tricyclic sesquiterpenes, with 7- β -H-silphiperfol-5-ene (5.7–14.9%), isocomene (2.8–14.4%), modhephene (2.3–9.9%), and 7- α -H-silphiperfol-5-ene (1.2–9.7%) being the predominant compounds [7, 8].

Approximately nine flavonoids have been isolated and identified from the aerial parts of *S. perfoliatum*, five of which have been studied in greater detail. These include isorhamnetin 3-O- α -L-rhamnopyranosyl-(1'''' \rightarrow 6''')-O- β -D-galactopyranoside 7-O- β -L-apiofuranoside, quercetin 3-O- α -L-rhamnopyranosyl-(1'''' \rightarrow 6''')-O- β -D-galactopyranoside 7-O- β -L-apiofuranoside, quercetin 3-O- β -L-galactosyl-(1'''' \rightarrow 6''')-O- β -D-rhamnopyranoside 7-O- α -L-apiofuranoside, kaempferol 3-O- β -D-apiofuranoside 7-O- α -L-rhamnopyranosyl-(1'''' \rightarrow 6''')-O- β -D-galactopyranoside, and kaempferol 3-O- β -D-apiofuranoside 7-O- α -L-rhamnopyranosyl-(1'''' \rightarrow 6''')-O- β -D-(2''''-O-E-caffeoyl)galactopyranoside [9].

S. perfoliatum is not used in official medicine. However, ethnopharmacological sources describe its use in the traditional medicine of Indigenous peoples of North America, where it has been employed for the treatment of neuralgia, colds, and rheumatic conditions [10]. Among the limited studies addressing its pharmacological activity, antimicrobial effects of leaf and root extracts against Gram-positive bacteria (*Enterococcus faecalis*, *Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli*, *Pseudomonas aeruginosa*) have been reported [11]. In addition, hepatoprotective activity has been demonstrated in laboratory mice, attributed to the presence of caffeoylquinic acid (CQA) compounds [12, 13].

Given the documented organ-specific variability in the qualitative and quantitative composition of terpenoids in *S. perfoliatum*, a systematic investigation of essential oil constituents from different plant organs is scientifically justified to elucidate potential structure-activity relationships, and identify organ-dependent chemotypes. Such studies are particularly relevant in view of the reported biological activities of terpenoid-rich fractions and the overall limited phytochemical characterisation of this species. Notably, *S. perfoliatum* raw material of Ukrainian origin has not been investigated to date, highlighting a knowledge gap and supporting the need for region-specific phytochemical profiling.

The aim of this study was to conduct a comprehensive analysis of the qualitative and quantitative composition of essential oils isolated from different organs of

S. perfoliatum L. to identify organ-dependent variations and expand current knowledge of the phytochemical profile of this species.

2. Planning (methodology) of research

The stages describing the study of raw material samples in this research are shown in Fig. 1.

Workflow of the Study

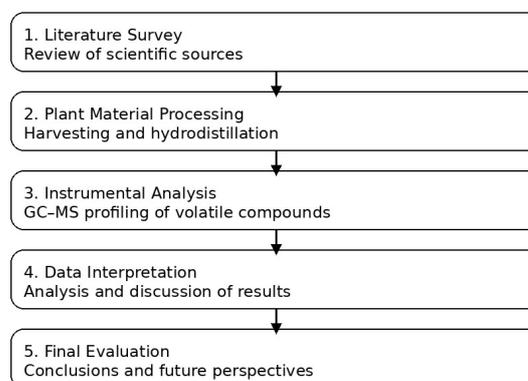


Fig. 1. Planning of research

3. Materials and methods

The plant material used in this study was collected from the experimental plots of the Faculty of Pharmacy, Department of Pharmaceutical Management, Drug Technology and Pharmacognosy, Ivano-Frankivsk National Medical University, Ivano-Frankivsk (IFNMU), Ukraine. The collection was carried out in 2023 (leaves) and in 2024 (leaves, aerial parts, flowers, and roots).

Leaves and aerial parts were harvested during the period of active growth of young shoots, flowers were collected at the stage of full flowering, and roots were harvested during the period of senescence of the aboveground parts of the plant. Botanical identification of the plant material was performed by Professor Andrii Hrytsyk [14]. Drying of the collected material was conducted according to standard procedures for terpenoid-containing raw materials [15]. The samples of raw plant materials and the herbaria (# 803-805) are stored in a dry, well-ventilated, light-protected place in the Department.

Analysis of Volatile Compounds by GC-MS.

Samples of volatile compounds (VCs) were obtained by hydrodistillation of dried *S. perfoliatum* plant material in accordance with the essential oil distillation method described in the European Pharmacopoeia [16]. The distilled VC samples were analysed by gas chromatography coupled with mass spectrometric detection (GC-MS) using an Agilent 6890/5973 GC-MS system operated with ChemStation software for mass-selective detectors (MSD) at the Institute of Pharmacy, University of Tartu, Tartu, Estonia.

An aliquot of 1 μ L of each sample was injected at an injector temperature of 280°C in split mode (10:1), using helium as the carrier gas, onto an Agilent HP-5ms UI capillary column (30 m \times 0.25 mm i.d., film thickness 0.25 μ m). The carrier gas flow rate was maintained

at a constant 1 mL/min. The oven temperature program was as follows: an initial temperature of 50°C held for 2 min, increased at 4°C/min to a final temperature of 280°C, which was maintained for 5 min (Fig. 2). This choice of GC column and GC-MS method has been previously developed and successfully applied by us for the identification and semi-quantitative analysis of volatile fractions from several plants [17–20].

The mass spectrometer was operated in electron ionisation (EI) mode at 70 eV. Mass spectra were recorded over the m/z range of 29–400, with a solvent delay of 4 min and a scan rate of 3.8 scans per second. Data processing was performed using the deconvolution algorithm of the Agilent MassHunter software package with variable window factors. Compound identification was carried out by comparison with the NIST23 mass spectral library using a match factor ≥ 90 and by calculation of retention indices relative to a homologous series of n-alkanes (C_7 – C_{30}) [21, 22]. The relative content of each compound was expressed as a percentage of the total peak area in the chromatograms without the use of correction factors. The total peak area is fixed after peak identification and does not account for

unidentified components. All listed compounds (Table 1) are terpenoid plant metabolites; however, some of them may also occur as secondary oxidation products or distillation artefacts.

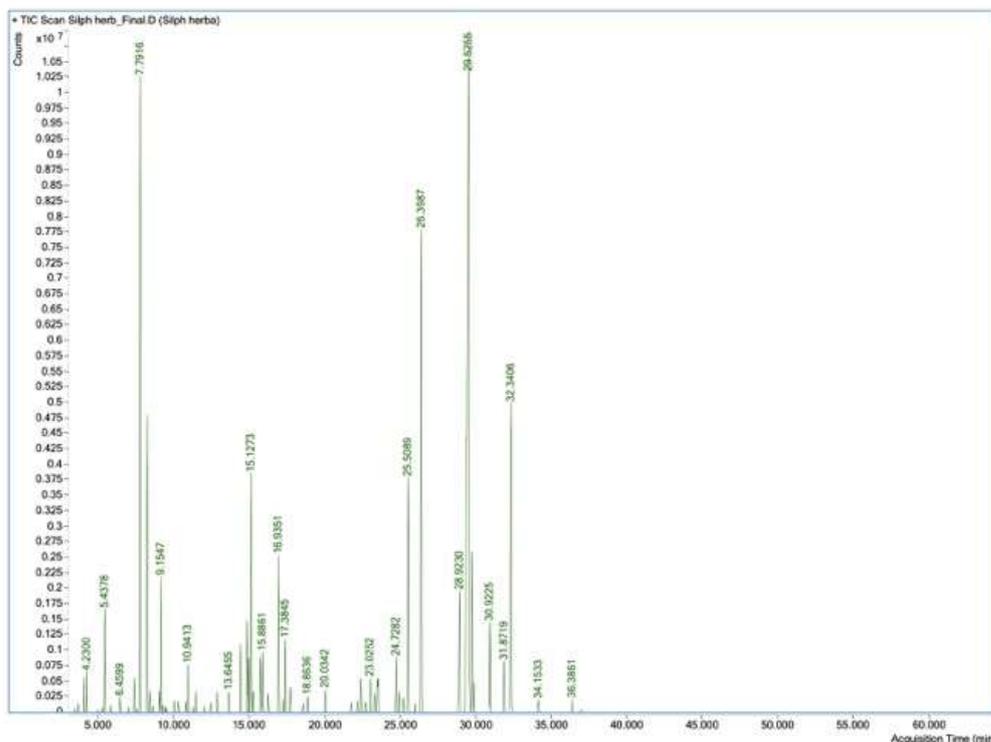


Fig. 2. GC-MS chromatogram of essential oil from *Silphium perfoliatum* herb
Rt 7.7919 – α -pinene; 26.3987 – β -copaene; 29.5255 – caryophyllene oxide

4. Results

The investigation identified 84 compounds in *S. perfoliatum* raw materials. Identified components of volatile fractions included monoterpenoids, sesquiterpenes, diterpenes, aldehydes and other aroma compounds (Table 1). The total content of terpenoids by classes in individual raw material samples is presented in Table 2.

Table 1

Content ($\geq 0.1\%$) of volatile compounds in distillates obtained from different organs of *Silphium perfoliatum*

Compound	Retention index		Formula	Content, %				
	MS	NIST30 Lib		Leaves 2023	Leaves 2024	Flos	Herb	Roots
1	2	3	4	5	6	7	8	9
Monoterpenes								
α-Pinene	932	935	$C_{10}H_{16}$	2.95	1.03	2.95	9.62	0.16
Camphene	946	948	$C_{10}H_{16}$	0.32	0.35	0.32	3.63	0.08
β -Phellandrene	972	973	$C_{10}H_{16}$	nd	nd	nd	0.25	nd
β -Pinene	975	976	$C_{10}H_{16}$	0.27	0.15	0.27	1.70	nd
<i>p</i> -Cymene	1023	1024	$C_{10}H_{14}$	<0.1	nd	<0.1	0.13	<0.1
Limonene	1027	1031	$C_{10}H_{16}$	0.21	0.11	0.21	0.59	nd
(<i>E</i>)-Pinocarveol	1137	1139	$C_{10}H_{16}O$	0.14	nd	0.14	1.29	nd
(<i>E</i>)-Verbenol	1143	1145	$C_{10}H_{16}O$	0.50	0.27	0.50	3.87	nd
Pinocarvone	1161	1162	$C_{10}H_{14}O$	<0.1	nd	<0.1	0.82	nd
Terpinen-4-ol	1176	1177	$C_{10}H_{18}O$	nd	nd	nd	0.25	nd
Myrtenal	1195	1196	$C_{10}H_{14}O$	0.23	0.12	0.23	2.11	nd
Safranal	1198	1201	$C_{10}H_{14}O$	0.59	<0.1	0.59	nd	nd
Verbenone	1208	1209	$C_{10}H_{14}O$	0.15	<0.1	0.15	1.02	nd
Carvone	1243	1242	$C_{10}H_{14}O$	nd	nd	nd	0.10	nd
Isobornyl acetate	1285	1285	$C_{12}H_{20}O_2$	0.83	0.16	0.83	0.31	nd

Continuation of Table 1

1	2	3	4	5	6	7	8	9
Salvia-4(14)-en-1-one	1598	1595	C ₁₅ H ₂₄ O	4.62	4.41	4.62	2.40	nd
Total,%				7.97	5.88	8.27	23.60	0.18
Sesquiterpenes								
Silphiperfol-5-ene	1327	1328	C ₁₅ H ₂₄	nd	nd	nd	nd	7.11
Presilphiperfol-7-ene	1334	1334	C ₁₅ H ₂₄	nd	nd	nd	nd	3.65
Silphinene	1349	1345	C ₁₅ H ₂₄	nd	nd	nd	nd	17.08
Copaene	1377	1376	C ₁₅ H ₂₄	0.48	nd	0.48	0.49	nd
β-Bourbonene	1386	1384	C ₁₅ H ₂₄	1.28	0.97	1.28	0.26	nd
Modephene	1389	1385	C ₁₅ H ₂₄	nd	nd	nd	nd	8.75
Elemene	1393	1395	C ₁₅ H ₂₄	1.65	nd	1.65	nd	nd
β-Isocomene	1416	1412	C₁₅H₂₄	nd	nd	nd	nd	12.71
Caryophyllene	1421	1419	C₁₅H₂₄	5.60	5.21	5.60	7.49	6.92
β-Cadinene	1431	1432	C ₁₅ H ₂₄	0.68	0.59	0.68	0.78	0.30
Humulene	1456	1454	C ₁₅ H ₂₄	2.56	2.29	2.56	3.60	4.26
Aristolochene	1472	1476	C ₁₅ H ₂₄	0.44	0.21	0.44	0.11	nd
γ-Muurolene	1472	1476	C ₁₅ H ₂₄	nd	0.21	nd	nd	nd
β-Copaene	1484	1486	C₁₅H₂₄	8.91	0.21	8.91	9.34	5.45
β-Bisabolene	1479	1477	C ₁₅ H ₂₄	nd	0.27	nd	nd	5.75
β-Nerolidol	1567	1564	C ₁₅ H ₂₆ O	3.19	0.28	3.19	nd	nd
4,8-Epoxyazulene	1571	1573	C ₁₅ H ₂₆ O	2.06	1.46	2.06	1.97	1.63
Humulene epoxide I	1604	1604	C ₁₅ H ₂₆ O	0.37	0.50	0.37	0.44	nd
Caryophyllene oxide	1589	1581	C₁₅H₂₄O	23.55	25.71	23.55	24.14	nd
Silphiperfol-6-en-5-one	1630	1624	C ₁₅ H ₂₂ O	nd	nd	nd	nd	1.34
ent-Germacra-4(15),5,10(14)-trien-1β-ol	1637	1642	C₁₅H₂₄O	nd	1.94	nd	5.91	nd
α-Bisabolol	1690	1684	C ₁₅ H ₂₆ O	nd	nd	nd	nd	0.91
Germacra-4(15),5,10(14)-trien-1β-ol	1691	1690	C₁₅H₂₄O	16.42	20.66	16.42	5.91	1.67
Total,%				67.19	60.51	67.19	60.44	77.53
Diterpenes								
Phytol	2114	2114	C₂₀H₄₀O	5.46	16.54	5.46	nd	nd
Aldehydes								
(E)-2-Heptenal	954	958	C ₇ H ₁₂ O	0.24	0.31	0.24	nd	nd
Hexanal	799	801	C ₆ H ₁₂ O	0.89	0.78	0.89	0.32	0.37
(E)-2,4-Hexadienal	909	911	C ₆ H ₈ O	nd	0.09	nd	0.05	0.03
1-Nonene	889	889	C ₉ H ₁₈	nd	<0.1	nd	0.13	nd
Nonane	899	900	C ₉ H ₂₀	nd	nd	nd	nd	nd
Oct-7-enal	995	996	C ₈ H ₁₄ O	nd	nd	nd	nd	0.35
Octanal	1003	1003	C ₈ H ₁₆ O	0.29	0.19	0.29	0.13	nd
(E,E)-2,4-Heptadienal	1009	1012	C ₇ H ₁₀ O	0.34	0.28	0.34	0.13	nd
Hyacinthin	1042	1045	C ₈ H ₈ O	<0.1	<0.1	<0.1	0.25	<0.1
(E)-2-Octenal	1056	1060	C ₈ H ₁₄ O	nd	0.16	nd	nd	<0.1
Nonanal	1103	1104	C ₉ H ₁₈ O	0.46	0.41	0.46	0.27	<0.1
Decanal	1204	1206	C ₁₀ H ₂₀ O	0.22	0.20	0.22	0.15	nd
2-Hexenal	848	851	C ₆ H ₁₀ O	1.78	1.54	1.78	1.00	<0.1
1-Hexanol	864	868	C ₆ H ₁₄ O	nd	<0.1	nd	<0.1	nd
1-Octene	792	789	C ₈ H ₁₆	nd	<0.1	nd	0.26	nd
δ-Cadinene	1528	1524	C ₁₅ H ₂₄	nd	nd	nd	nd	1.06
1-Pentadecene	1494	1492	C ₁₅ H ₃₀	nd	nd	nd	nd	1.87
Aplotaxene	1674	1664	C ₁₇ H ₂₈	nd	nd	nd	nd	5.75
Tricyclene	921	925	C ₁₀ H ₁₆	nd	nd	nd	0.39	0.40
Total,%				7.72	4.36	7.72	3.18	10.39
Other compounds								
(Z)-2-(2-Pentenyl)furan	1001	1002	C ₉ H ₁₂ O	nd	0.13	nd	nd	nd
2-Pentylfuran	991	993	C ₉ H ₁₄ O	0.41	0.30	0.41	0.22	nd
Sulcatone	986	986	C ₈ H ₁₄ O	0.15	<0.1	0.15	<0.1	nd
β-Cyclocitral	1220	1220	C ₁₀ H ₁₆ O	0.36	0.33	0.36	0.16	nd
D-Elemene	1342	1339	C ₁₅ H ₂₄	nd	nd	nd	0.13	6.40
1-Octen-3-ol	978	980	C ₈ H ₁₆ O	<0.1	0.17	<0.1	<0.1	nd
(E)-Longipinene	1351	1353	C ₁₅ H ₂₄	nd	nd	nd	0.19	1.29

Continuation of Table 1

1	2	3	4	5	6	7	8	9
<i>p</i> -Cymene	1023	1024	C ₁₀ H ₁₄	<0.1	nd	<0.1	0.13	<0.1
Eugenol	1357	1361	C ₁₀ H ₁₂ O ₂	nd	0.51	nd	0.49	nd
α -Campholenal	1125	1126	C ₁₀ H ₁₆ O	0.14	nd	0.14	0.91	nd
<i>p</i> -Mentha-1,5-dien-8-ol	1165	1167	C ₁₀ H ₁₆ O	<0.1	<0.1	<0.1	0.81	nd
Silphiperfol-4,7(14)-diene	1359	1361	C ₁₅ H ₂₂	nd	nd	nd	nd	0.54
2-Undecenal	1363	1367	C ₁₁ H ₂₀ O	0.09	0.24	<0.1	nd	nd
Dehydrosabinene	952	956	C ₁₀ H ₁₄	nd	nd	nd	0.24	nd
Cyclosativene	1367	1368	C ₁₅ H ₂₄	nd	nd	nd	0.18	nd
Germacrene D	1447	1448	C ₁₅ H ₂₄	nd	nd	nd	0.19	0.10
5-Cyclodecen-1-ol	1484	1486	C ₁₅ H ₂₄	nd	3.67	nd	0.30	nd
epi- β -Selinene	1489	1490	C ₁₅ H ₂₄	1.88	nd	1.88	nd	nd
11,11-Dimethyl-4,8-dimethylenebicyclo[7,2,0]undecan-3-ol	1641	1646	C ₁₅ H ₂₄ O	0.79	1.46	0.79	1.38	nd
Caryophylla-4(12),8(13)-dien-5- β -ol	1641	1642	C ₁₅ H ₂₄ O	nd	1.94	nd	1.49	nd
Dihydro-aplotaxene	1667	1665	C ₁₇ H ₃₀	nd	nd	nd	nd	2.98
Pentadecanal	1715	1715	C ₁₅ H ₃₀	nd	nd	nd	0.03	nd
Ylangenol	1760	1760	C ₁₅ H ₂₄ O	1.05	1.71	1.05	0.20	0.33
2-Naphthalenemethanol	1806	1803	C ₁₅ H ₂₄ O	0.26	nd	0.26	nd	0.22
Hexahydrofarnesyl acetone	1851	1844	C ₁₈ H ₃₆ O	3.31	1.26	3.31	0.14	nd
Pentacosane	2500	2500	C ₂₅ H ₅₂	nd	nd	nd	nd	nd
Total,%				8.74	11.92	8.75	7.39	11.96
Content of EO, mL/kg				2.66	3.31	5.46	3.25	2.80

Note: Bold – >5%, nd – not detected.

Table 2

Total content of terpenoids by classes in the studied raw material samples

Compound class	Leaves 2023		Leaves 2024		Flos		Herb		Roots	
	Number of compounds	Compound content,%								
Monoterpenoids	13	27.08%	10	19.61%	13	27.08%	15	26.32%	3	8.33%
Sesquiterpenes	15	31.25%	15	29.41%	15	31.25%	14	24.56%	13	36.11%
Diterpenes	1	2.08%	1	1.96%	1	2.08%	0	0	0	0
Aldehydes	9	18.75%	13	25.49%	9	18.75%	12	21.05%	12	33.33%
Other aroma compounds	10	20.08%	12	23.53%	10	20.08%	16	28.07%	8	22.23%
Total	48		51		48		57		36	

5. Discussion

The GC-MS analysis revealed pronounced qualitative and quantitative differences in the volatile profiles of *S. perfoliatum* across plant organs. Sesquiterpenes were the dominant class of compounds in all samples, accounting for 60.44–77.53% of the total volatile fraction. Caryophyllene oxide, germacrene-type alcohols, and caryophyllene were identified as the major constituents in the aerial parts, whereas the root distillates were characterised by a high abundance of silphiperfol derivatives, including silphiperfol-5-ene, presilphiperfol-7-ene, silphinene, and isocomene. Monoterpenes were most abundant in the flowers (23.60%), with α -pinene, camphene, and oxygenated monoterpenes contributing substantially to the volatile profile, while their content in roots was negligible. Diterpenes were represented mainly

by phytol and were detected predominantly in leaves, whereas aldehydes and other minor compounds contributed modestly to the overall composition, further emphasizing the organ-specific specialisation of volatile biosynthesis in *S. perfoliatum*.

A comparative analysis of the essential oil composition of *S. perfoliatum* leaves collected in 2023 and 2024 revealed both qualitative stability and notable quantitative differences. In both years, sesquiterpenes constituted the dominant class of volatile compounds, accounting for 67.19% and 60.51% of the total oil content in 2023 and 2024, respectively, indicating a consistent biosynthetic preference for sesquiterpene production in leaf tissues. Caryophyllene oxide and germacrene-type alcohols remained the major constituents in both samples; however, their relative abundance was higher in the 2024

leaves, accompanied by an increased contribution of diterpenes, primarily phytol (16.54% in 2024 vs 5.46% in 2023). In contrast, the 2023 leaf samples were characterized by a higher proportion of monoterpenes (7.97% vs 5.88%) and aldehydes (7.72% vs 4.36%), suggesting a shift toward more oxidized and low-molecular-weight volatiles in that season. Overall, these results indicate that while the qualitative profile of leaf essential oils remains relatively stable between years, interannual variations significantly influence the quantitative distribution of terpenoid classes, likely reflecting differences in environmental conditions and plant physiological status during the growing season.

In the samples of aerial parts of *S. perfoliatum*, a common set of volatile constituents is observed, including α -pinene, caryophyllene, caryophyllene oxide, and phytol (flowers and leaves). In contrast, the chemical profile of the roots differs markedly: the root material is dominated by the sesquiterpenes silphiperfol-5-ene, caryophyllene, β -selinene, and β -bisabolene. Comparative analysis of the essential oil composition of *S. perfoliatum* collected from different plant organs (leaves 2024, flowers, aerial parts, and roots) revealed pronounced organ-specific differences in both qualitative and quantitative profiles. Leaves and aerial parts were characterised by a predominance of sesquiterpenes (60.51% and 60.44%, respectively), with caryophyllene oxide, caryophyllene, humulene, and germacrene-type alcohols as the major constituents, indicating a shared biosynthetic pattern in photosynthetically active tissues. The predominance of sesquiterpenes is consistent with numerous studies demonstrating that caryophyllane-type sesquiterpenoids exhibit diverse biological activities, including anti-inflammatory, immunomodulatory, and chemopreventive effects, thereby highlighting their potential pharmacological relevance in essential oils [23–25].

Flowers exhibited a markedly higher proportion of monoterpenes (23.60%), dominated by α -pinene, camphene, and oxygenated monoterpenes, reflecting the role of floral volatiles in ecological interactions such as pollinator attraction. These monoterpenoids exhibit diverse pharmacological activities, including antimicrobial, anti-inflammatory, antioxidant, and analgesic effects, suggesting that the elevated monoterpene content may contribute to the biological potential of flower essential oils [26, 27]. In contrast, root essential oils showed a distinct chemotype dominated by sesquiterpene hydrocarbons (77.53%), particularly silphiperfol derivatives (silphiperfol-5-ene, presilphiperfol-7-ene, silphinene, and isocomene), while monoterpenes were nearly absent. Triquinane-type sesquiterpenoids related to silphiperfol derivatives have been reported to exhibit diverse biological effects, including antimicrobial, cytotoxic, and other bioactivities in natural product studies, suggesting that the high abundance of silphiperfol-type sesquiterpenes in *S. perfoliatum* roots may contribute to similar pharmacological potential deserving further evaluation [28, 29]. Additionally, diterpenes were detected mainly in leaves, whereas aldehydes and other minor compounds contributed modestly and variably across organs. Overall, these find-

ings demonstrate a clear organ-dependent specialisation of terpenoid biosynthesis in *S. perfoliatum*, with aboveground organs favouring oxygenated sesquiterpenes and monoterpenes, and roots accumulating structurally complex sesquiterpene hydrocarbons.

When compared with previously published data on the essential oil composition of *S. perfoliatum*, several consistent patterns and notable differences emerge. Kowalski and Wolski reported that the leaf essential oil of *S. perfoliatum* was dominated by the sesquiterpene caryophyllene oxide (8.5–34.7%) and the sesquiterpene germacrene D (6.4–24.3%), while the inflorescence oil contained higher proportions of the monoterpene α -pinene (16.0–20.9%) [7, 8]. These findings are broadly aligned with our observations, as sesquiterpenes such as caryophyllene oxide and germacrene-type compounds also feature prominently in our leaf and aerial parts samples, though their relative abundances vary between organs. However, in contrast to the earlier work, our results indicate a much higher total sesquiterpene content in roots (77.53%) and a distinct terpene profile with substantial amounts of silphiperfol derivatives that were either absent or present at lower levels in the Polish material [8].

Additionally, the proportion of monoterpenes in our flower samples is notably higher than in previously reported inflorescence oils, suggesting that organ-specific, and potentially environment- or genotype-dependent, variation in volatile composition is significant in *S. perfoliatum*. These differences underscore the influence of collection site, harvest time, and genetic background on essential oil composition and highlight the importance of region-specific chemoprofiling in future studies.

Practical relevance. The present study expands current knowledge on the volatile profiles of *S. perfoliatum* by providing a detailed organ-specific characterization of essential oil constituents in leaves, flowers, aerial parts, and roots. Eighty-four volatile compounds were detected, including a number of sesquiterpenes, particularly silphiperfol-related hydrocarbons in root samples, that have been poorly documented or insufficiently characterised in earlier investigations. The revealed differences in the distribution of terpenoid classes among plant organs highlight the potential for selective use of *S. perfoliatum* raw materials and create a rationale for their further exploration as promising sources of biologically active substances with possible pharmaceutical, cosmetic, or industrial relevance. The study supports organ-specific differentiation of *S. perfoliatum* raw materials and highlights the need for controlled harvesting. The GC-MS dataset provides a reference for future quality-oriented and applied investigations.

Research limitations. The study was based on GC-MS profiling with relative quantification, which may limit discrimination of closely related compounds. As the material was collected from a single location, further studies are needed to assess geographical variability.

Prospects for further research. Considering the significant presence of terpenoid compounds such as caryophyllene oxide, germacrene-derived alcohols, silphiperfol-type sesquiterpenes, phytol, and selected monoter-

penes, further in-depth studies of *S. perfoliatum* appear well justified. Future research should include isolation and structural confirmation of major constituents, systematic evaluation of their biological and pharmacological activities, and assessment of seasonal, ecological, and geographical influences on volatile composition. Additionally, investigation of possible synergistic effects within organ-specific essential oil fractions may facilitate the development of novel plant-based products and broaden the practical applications of this species.

Based on the predominance of oxygenated sesquiterpenes, monoterpenes, and silphiperfol-type sesquiterpenoids in different plant organs, future studies may focus on the evaluation of anti-inflammatory, antimicrobial, and cytotoxic activities of organ-specific essential oil fractions. Particular attention should be given to the root essential oil as a source of structurally unique sesquiterpenes and to the potential synergistic effects within complex volatile mixtures.

6. Conclusions

This study provides a detailed characterisation of the volatile composition of *S. perfoliatum* collected from different plant organs and harvest years, revealing pronounced organ-specific and interannual variability. The content of volatile fractions varied from 2.66 to 5.46 mL/kg, depending on the plant organs. A total of 84 volatile compounds were identified, with sesquiterpenes representing the dominant class in all samples (60.44–77.53%). Aboveground organs were characterized by a prevalence of oxygenated sesquiterpenes, particularly caryophyllene oxide and germacrene-type alcohols, whereas roots exhibited a distinct chemotype dominated by silphiperfol-type sesquiterpene hydrocarbons. Monoterpenes were most abundant in the flowers (23.60%), with α -pinene, camphene, and oxygenated monoterpenes contributing substantially to the volatile profile, while their content in roots was negligible. Comparative analysis of leaf samples collected in 2023 and 2024 demonstrated qualitative stability of the volatile profile accompanied by significant quantitative shifts in terpenoid classes, indicating the influence of environmental and physiological factors. Overall, these findings expand current knowledge of the phytochemical diversity of *S. perfolia-*

tum and provide a foundation for further studies on the biological relevance and potential applications of its essential oils.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this article.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Liubomyr Lytvynets: Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; **Andriy Grytsyk:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization; **Ivan Bilai:** Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing; **Oleh Koshovyi:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision; **Ain Raal:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

References

1. Britton, N. L., Brown, A. (1913) An illustrated flora of the northern United States, Canada and the British possessions: from Newfoundland to the parallel of the southern boundary of Virginia, and from the Atlantic Ocean westward to the 102d meridian. New York . <https://doi.org/10.5962/bhl.title.940>
2. *Silphium perfoliatum*. Flora of North America. Available at: http://www.efloras.org/florataxon.aspx?flora_id=1&taxon_id=242417268
3. Albrecht, K. A., Goldstein, W. (1997). *Silphium perfoliatum*: A North American Prairie Plant with Potential as a Forage Crop. The XVIII International Grassland Congress. Winnipeg.
4. *Silphium perfoliatum*. Royal Botanic Gardens. Available at: <https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:236461-2>
5. Ende, L. M., Knöllinger, K., Keil, M., Fiedler, A. J., Lauerer, M. (2021). Possibly Invasive New Bioenergy Crop *Silphium perfoliatum*: Growth and Reproduction Are Promoted in Moist Soil. *Agriculture*, 11 (1), 24. <https://doi.org/10.3390/agriculture11010024>
6. Kowalski, R., Wolski, T. (2003). Evaluation of phenolic acid content in *Silphium perfoliatum* L. leaves, inflorescences and rhizomes. *Electronic Journal of Polish Agricultural Universities*, 6 (1).

7. Kowalski, R., Wolski, T. (2005). The chemical composition of essential oils of *Silphium perfoliatum* L. Flavour and Fragrance Journal, 20 (3), 306–310. <https://doi.org/10.1002/ffj.1418>
8. Kowalski, R., Wierciński, J., Mardarowicz, M. (2005). Essential Oil in Leaves and Inflorescences of *Silphium integrifolium-Michx.* Journal of Essential Oil Research, 17 (2), 220–222. <https://doi.org/10.1080/10412905.2005.9698881>
9. Williams, J. D., Wojcińska, M., Calabria, L. M., Linse, K., Clevinger, J. A., Mabry, T. J. (2009). The Flavonoids and Phenolic Acids of the Genus *Silphium* and Their Chemosystematic Value. Natural Product Communications, 4 (3). <https://doi.org/10.1177/1934578x0900400325>
10. Gilmore, M. R. (1919). Uses of plants by the Indians of the Missouri River region. Lincoln: University of Nebraska Press. <https://doi.org/10.5962/bhl.title.32507>
11. Kowalski, R., Kędzia, B. (2007). Antibacterial Activity of *Silphium perfoliatum*. Extracts. Pharmaceutical Biology, 45 (6), 494–500. <https://doi.org/10.1080/13880200701389409>
12. Zhang, G., Jia, W., Liu, L., Wang, L., Xu, J., Tao, J. et al. (2025). Caffeoylquinic acids from *Silphium perfoliatum* L. show hepatoprotective effects on cholestatic mice by regulating enterohepatic circulation of bile acids. Journal of Ethnopharmacology, 337, 118870. <https://doi.org/10.1016/j.jep.2024.118870>
13. Xu, J., Jia, W., Zhang, G., Liu, L., Wang, L., Wu, D. et al. (2024). Extract of *Silphium perfoliatum* L. improve lipid accumulation in NAFLD mice by regulating AMPK/FXR signaling pathway. Journal of Ethnopharmacology, 327, 118054. <https://doi.org/10.1016/j.jep.2024.118054>
14. Dobrochaeva, D. N., Kotov, M. Y., Prokudyn, Yu. N., Barbarych, A. Y. (1999). Opredeľitel vysshikh rastenyi Ukrainy. Kyiv: Naukova Dumka.
15. EMEA/HMPC/246816/2005. Guideline on Good Agricultural and Collection Practice (GACP) for Starting Materials of Herbal Origin (2006). European Medicines Agency.
16. European Pharmacopoeia (2022). Strasbourg: Council of Europe.
17. Raal, A., Ilina, T., Kovalyova, A., Koshovyi, O. (2024). Volatile compounds in distillates and hexane extracts from the flowers of *Philadelphus coronarius* and *Jasminum officinale*. ScienceRise: Pharmaceutical Science, 6 (52), 37–46. <https://doi.org/10.15587/2519-4852.2024.318497>
18. Raal, A., Dolgošev, G., Ilina, T., Kovalyova, A., Lepiku, M., Grytsyk, A., Koshovyi, O. (2025). The Essential Oil Composition in Commercial Samples of *Verbena officinalis* L. Herb from Different Origins. Crops, 5 (2), 16. <https://doi.org/10.3390/crops5020016>
19. Raal, A., Liira, J., Lepiku, M., Ilina, T., Kovalyova, A., Strukov, P. et al. (2025). The Composition of Essential Oils and the Content of Saponins in Different Parts of *Gilia capitata* Sims. Crops, 5 (3), 33. <https://doi.org/10.3390/crops5030033>
20. Hrytsyk, Y., Koshovyi, O., Lepiku, M., Jakštas, V., Žvikas, V., Matus, T. et al. (2024). Phytochemical and Pharmacological Research in Galenic Remedies of *Solidago canadensis* L. Herb. Phytion, 93 (9), 2303–2315. <https://doi.org/10.32604/phyton.2024.055117>
21. Raal, A., Komarov, R., Orav, A., Kapp, K., Grytsyk, A., Koshovyi, O. (2022). Chemical composition of essential oil of common juniper (*Juniperus communis* L.) branches from Estonia. ScienceRise: Pharmaceutical Science, 6 (40), 66–73. <https://doi.org/10.15587/2519-4852.2022.271048>
22. Sepp, J., Koshovyi, O., Jakštas, V., Žvikas, V., Botsula, I., Kireyev, I. et al. (2024). Phytochemical, Pharmacological, and Molecular Docking Study of Dry Extracts of *Matricaria discoidea* DC. with Analgesic and Soporific Activities. Biomolecules, 14 (3), 361. <https://doi.org/10.3390/biom14030361>
23. Francomano, F., Caruso, A., Barbarossa, A., Fazio, A., La Torre, C., Ceramella, J. et al. (2019). β -Caryophyllene: A Sesquiterpene with Countless Biological Properties. Applied Sciences, 9 (24), 5420. <https://doi.org/10.3390/app9245420>
24. Baradaran Rahimi, V., Askari, V. R. (2022). A mechanistic review on immunomodulatory effects of selective type two cannabinoid receptor β -caryophyllene. BioFactors, 48 (4), 857–882. <https://doi.org/10.1002/biof.1869>
25. Baradaran Rahimi, V., Memarzia, A., Askari, V. R. (2023). Antiinflammatory and antioxidant and immunomodulatory effects of phytocannabinoid β -caryophyllene: A mechanistic review. Medicinal Usage of Cannabis and Cannabinoids. Elsevier, 349–359. <https://doi.org/10.1016/b978-0-323-90036-2.00010-7>
26. Salehi, B., Upadhyay, S., Erdogan Orhan, I., Kumar Jugran, A., L. D. Jayaweera, S., A. Dias, D. et al. (2019). Therapeutic Potential of α - and β -Pinene: A Miracle Gift of Nature. Biomolecules, 9 (11), 738. <https://doi.org/10.3390/biom9110738>
27. Zielińska-Błajet, M., Feder-Kubis, J. (2020). Monoterpenes and Their Derivatives – Recent Development in Biological and Medical Applications. International Journal of Molecular Sciences, 21 (19), 7078. <https://doi.org/10.3390/ijms21197078>
28. Cheekatla, S. R. (2024). Triquinane based natural products via cycloadditions and metathesis. Tetrahedron Chem, 12, 100103. <https://doi.org/10.1016/j.tchem.2024.100103>
29. Qiu, Y., Lan, W.-J., Li, H.-J., Chen, L.-P. (2018). Linear Triquinane Sesquiterpenoids: Their Isolation, Structures, Biological Activities, and Chemical Synthesis. Molecules, 23 (9), 2095. <https://doi.org/10.3390/molecules23092095>

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Liubomyr Lytvynets, Assistant, Department of Pharmaceutical Management, Drug Technology and Pharmacognosy, Ivano-Frankivsk National Medical University, Halytska str., 2, Ivano-Frankivsk, Ukraine, 76018
ORCID: <https://orcid.org/0009-0006-7765-0417>

Andriy Grytsyk, Doctor of Pharmaceutical Sciences, Professor, Head of Department, Department of Pharmaceutical Management, Drug Technology and Pharmacognosy, Ivano-Frankivsk National Medical University, Halytska str., 2, Ivano-Frankivsk, Ukraine, 76018
ORCID: <https://orcid.org/0000-0001-7335-887X>

Ivan Bilai, Doctor of Pharmaceutical Sciences, Professor, Head of Department, Department of Clinical Pharmacy, Pharmacotherapy, Pharmacognosy and Pharmaceutical Chemistry, Educational and Scientific Institute of Postgraduate Education, Zaporizhzhia State Medical and Pharmaceutical University, Marii Prymachenko blvd., 26, Zaporizhzhia, Ukraine, 69035
ORCID: <https://orcid.org/0000-0002-7574-4093>

Oleh Koshovyi, Doctor of Pharmaceutical Sciences, Professor, Institute of Pharmacy, University of Tartu, Nooruse str., 1, Tartu, Estonia, 50411, Professor, Department of Clinical Pharmacy, Pharmacotherapy, Pharmacognosy and Pharmaceutical Chemistry, Zaporizhzhia State Medical and Pharmaceutical University, Marii Prymachenko blvd., 26, Zaporizhzhia, Ukraine, 69035
ORCID: <https://orcid.org/0000-0001-9545-8548>

Raal Ain*, PhD, Professor, Institute of Pharmacy, University of Tartu, Nooruse str., 1, Tartu, Estonia, 50411
ORCID: <https://orcid.org/0000-0001-8731-7366>

**Corresponding author: Raal Ain, e-mail: ain.raal@ut.ee*