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Article

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Abstract

Sumatra camphor (*Dryobalanops aromatica* Gaertn.) is a high-value non-timber forest product (NTFP) traditionally harvested by forest-dependent communities in northern Sumatra, Indonesia. Despite its extensive ethnobotanical utilization in medicinal and olfactory applications, scientific data on its phytochemical composition remain limited. This study aims to characterize the physical and phytochemical properties of Sumatra camphor oleoresin, collected from natural population in the Pakpak Bharat of Sumatra, one of few remaining endemic habitats for this vulnerable species. Using traditional oleoresin extraction methods, two fractions—camphor oil and aqueous camphor—were collected and analysed. Phytochemical identification was conducted using gas chromatography–mass spectrometry. The analysis identified 79 compounds in camphor oil and 11 in the aqueous fraction, each with distinct profiles. Camphor oil was dominated by non-polar volatile compounds with pronounced olfactory properties and prospects bioactive activities, while aqueous camphor contained polar compounds such as carboxylic acids, esters, and alcohols, which have pharmacological and functional potential. These findings provide scientific evidence supporting the traditional utilization of Sumatran camphor and its bioactive potential for valorisation in plant-based cosmetic products, aromatherapy, and pharmaceutical industries. Furthermore, the results contribute to conservation-based bioeconomic strategies for managing Sumatra camphor sustainably as part of community-based forest management systems in Indonesia.

Keywords: aqueous camphor; aromatic; camphor oil; hydrocarbon; GC-MS; oleoresin; phytochemical composition; Sumatra camphor

1. Introduction

Indonesia is one of the world's largest tropical forest ecosystems, with approximately 95,5 million hectares of forest cover—nearly half of the country's land area [1]. This rich biodiversity

supports thousands of vascular plant species—around 29,375 species, with approximately 60% endemism [2]. The history of national development in Indonesia is closely tied to forest management practices [3,4]. However, forest loss and degradation—amounting to tens of millions of hectares over the past two decades [1,5,6]—have undermined the ecosystem's capacity to provide timber, non-timber forest products (NTFPs), and environmental services, contributing to socio-economic vulnerability among forest-dependent communities [3,4].

The Indonesian government has developed a forest management scheme that emphasises active community involvement, with NTFPs as the main commodity—as outlined in Minister of Forestry Regulation No. 35 of 2007. This initiative aims to combat the forest degradation rate by developing alternative local community income source from forest that does not involve cutting down trees [3,4,7]. Among various NTFP practices, camphor oleoresin extraction has long been a livelihood source of communities' livelihood on the west coast of Sumatra.

Natural camphor oleoresin, also known locally as *kapur barus*, is an NTFP that has been commercially exploited, even before the Dutch East Indies period. Historical records from the colonial era indicate that this forest-derived product was primarily sourced from the Barus and Singkil regions, located along the western coastal area of Sumatra [8,9]. The oleoresin from Sumatran camphor tree (*Dryobalanops aromatica* Gaertn) has been used commercially as a medicinal ingredient, natural preservative, fragrance, and part of cultural rituals [9,10].

Due to the harvesting scheme that employs non-destructive methods, camphor oleoresin offers excellent potential in community-based forest management systems. However, in-depth scientific studies on the physical characteristics and phytochemical content of Sumatran camphor oleoresin are limited [9,11,12]. This contrasts with the extensive investigation on *Cinnamomum camphora*, a species originating from East Asia [9,13–18]. Different from the extraction process in *C. camphora*, where camphor oil is currently obtained from leaf distillation [13–16], in *D. aromatica*, camphor oleoresin is exuded through fluid flowing from the resin ducts in response to mechanical injury [9,10,19].

Sumatran camphor has been a highly prized global commodity since the seventh century [20]. Recognising the physical properties and phytochemical composition remains relevant, particularly for enhancing its pharmacological potential. These analyses allow the identification of active compounds with significant pharmacological and aromatic properties [14,16,17]. The increasing demand for natural bioactive compounds is driven by global health awareness [21,22]. Sumatran camphor, supported by traditional knowledge on ethnomedicinal applications, is a promising candidate for the development of future medicines, aromatherapy products, and cosmetics.

There is a growing need for this research, especially considering the conservation status of *D. aromatica*, which is classified as vulnerable, previously critically endangered by the IUCN Red List [9,11,12]. In natural habitat, this endemic species continues to experience population reductions due to pressures from deforestation, illegal logging, and land conversion, particularly in the tropical rainforests of Sumatra [9]. This situation calls for evidence-based conservation efforts, including an understanding of the phytochemical content of oleoresins, which serves as the basis for designing conservation strategies through a bioeconomic approach and sustainable NTFP management.

The objective of the study is to characterize the physical and phytochemical properties of Sumatran camphor oleoresin across different quality grades. This research aims to provide scientific insight into a high-value endemic NTFP that is currently under sustainability threat, and to support the development of a sustainable local bioindustry within a community-based forest management system in Indonesia.

2. Results and Discussion

2.1. Oleoresin Harvesting

Traditionally, local communities in Pakpak Bharat, North Sumatra, use two methods to harvest camphor oleoresin. Although both involve mechanically disrupting the resin duct, there are differences between these techniques, based on the oleoresin yield: oil (balsam) or aqueous-like oleoresin fraction. A 10 cm deep notch is made at the tree base (100-130 cm above ground) to obtain

camphor oil. As a result, a slow-flowing balsam fluid (known locally as ombil) will exude from the notch. Whereas aqueous-like oleoresin fraction, namely aqueous camphor, is obtained through a shallower V-shaped incision (3-5 cm deep) made at a height of 100-130 cm above ground, and a horizontal cut at a height of 3-5 m with the same depth, orthogonal to the base incision point (Figure 4). Due to gravity, in a V-shaped tapping, the fluid in tapped resin duct will exude aqueous camphor at a faster flow rate than camphor oil. The harvested trees typically exhibit a minimum diameter of 40 cm.

Based on tapping on each of five sample trees using these two techniques, aqueous camphor and camphor oil were harvested, with the yields, collection time, and physical properties of oleoresin as in Table 1.

Table 1. Sumatra camphor oleoresin production.

Sample	Diameter (cm)	Aqueous camphor				Camphor oil			
		Time (minutes)	Yield (ml)	Flow rate (ml/min)	Viscosity (cP)	Time (minutes)	Yield (ml)	Flow rate (ml/min)	Viscosity (cP)
Tree 1	52	4.52	722	159.85	1.713	305	96	0.315	6.579
Tree 2	48	3.90	678	173.85	1.648	264	87	0.330	5.325
Tree 3	54	4.15	712	171.57	1.675	286	91	0.318	5.914
Tree 4	50	3.78	664	175.51	1.613	248	81	0.327	4.072
Tree 5	48	4.10	720	175.61	1.549	284	94	0.331	3.225

Time is measured starting from the trunk tapping is completed until the final drop of oleoresin is gathered.

Table 1 shows that the diameters of the harvested trees range from 48 to 54 cm. Figure 1 shows that there was no significant correlation between tree diameter and production of aqueous camphor or camphor oil, as the largest diameter tree (Tree 3) had an aqueous camphor yield of 712 ml and an oil yield of 91 ml, while the smallest diameter tree (Tree 5) had a slightly higher oil yield (94 ml). These findings indicate that other factors, such as tissue age, internal pressure, tree health, and secondary metabolic processes in the plant itself, may influence oleoresin production.

Extended collection times did not necessarily correlate with increased yields. Tree 5 recorded the highest flow rate (175.61 ml/min), with an aqueous camphor yield of 720 ml in 4.10 minutes. Conversely, Tree 1, with the longest time (4.52 minutes), exhibits the lowest flow rate (159.85 ml/min). Despite the longer harvest time (248–305 minutes), the flow rate in camphor oil is around 0.315–0.331 ml/min. Tree 5 had an oil yield of up to 94 ml and a flow rate of 0.331 ml/min with a harvest time of 284 minutes, while Tree 1 had the lowest flow rate (0.315 ml/min) with the longest harvest time (305 minutes).

The weak correlation between harvesting time and the yield of both aqueous camphor and oil is also influenced by the saturation point of the compound present in the tapped resin ducts, as well as its viscosity. The average flow rate of aqueous camphor (± 170 ml/min) is much higher than that of camphor oil (± 0.3 ml/min), as low-viscosity fluids exhibit enhanced flow characteristics through narrow resin duct. Figure 1 illustrates an inverse relationship between viscosity and flow rate, consistent with the principle of fluid dynamics that lower viscosity results in faster flow.

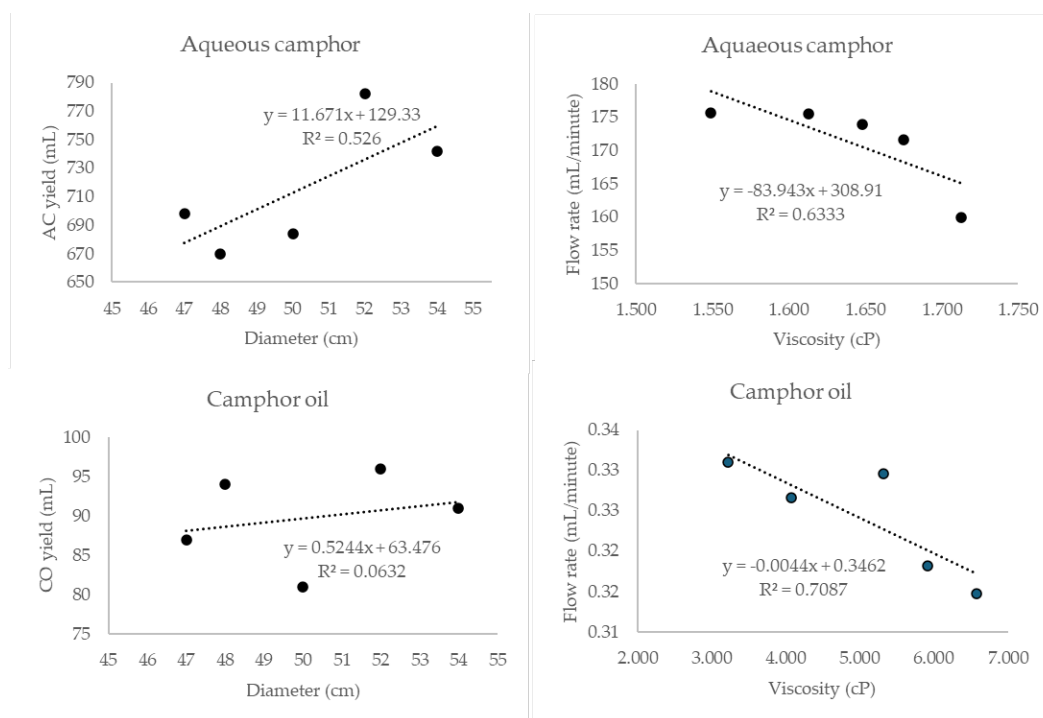


Figure 1. Relationship between tree diameter, viscosity and flow rate.

Based on Table 1, Tree 5 exhibited low viscosity and the highest flow rate, indicating that the aqueous camphor was more fluid and higher flow velocity. In comparison, Tree 1 exhibits the highest viscosity (1.713 cP) and the lowest flow rate, which may be attributed to a higher concentration of active components or differences in compound composition. In general, when viscosity is lower, friction against the resin duct walls is reduced, resulting in increased flow speed. Conversely, more viscous oleoresins tend to lower flow velocity. They are more easily retained and accumulated in the resin ducts, which can eventually lead to saturation or blockage, thereby extending the oleoresin collection time e.

Camphor oil shows higher viscosity than aqueous camphor, in accordance with the natural properties of oils that are thicker than aqueous fractions. The highest oil yield (96 ml) with the highest viscosity (6.579 cP) and the lowest flow rate (0.315 ml/minutes) was shown by Tree 1, indicating that camphor oil rich in heavier compounds requires more time. In contrast, Tree 5 yielded slightly less oil compared to Tree 1 but exhibited the lowest viscosity. Consequently, lower viscosity and reduced molecular weight fractions contributed to a higher flow rate (0.331 ml/min), enhancing oleoresin mobility through the resin duct system. These results confirm that higher viscosity is associated with increased flow resistance [23,24]. Viscosity variations suggest distinctions in physical properties attributed to chemical composition or molecular structure. In general, viscosity increases with larger molecular size and weight, as higher weight fractions contribute to greater specific gravity.

2.3. Analysis of Phytochemical Component

This study identified 79 volatile compounds through GC-MS-based chemical profiling on camphor oil samples from five trees (Figure 2). These compounds were grouped into eight major chemical classes, predominantly composed of hydrocarbons, followed by alcohols, ketones, aldehydes, esters, ethers, oxides, and carboxylic acids, respectively. The hydrocarbon compounds were identified as monoterpenes, sesquiterpenes, and oxygenated hydrocarbons, which contribute significantly to the aroma profile, and exhibit various biological activity, and pharmacological properties.

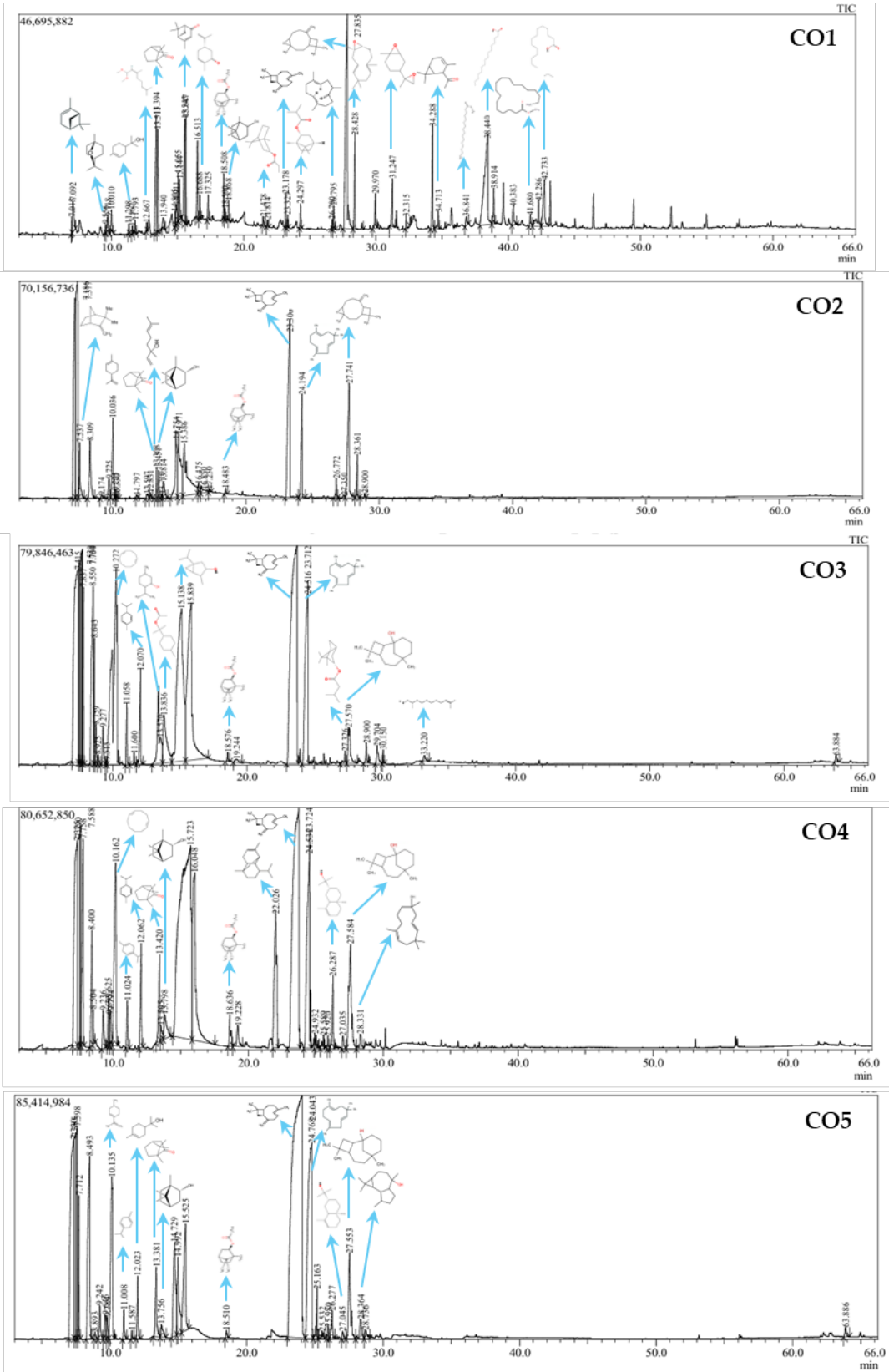


Figure 2. GC-MS of Sumatra camphor oil.

Table 2 presents the monoterpene identified, including α -pinene, β -pinene, camphene, β -ocimene, myrcene, and d-limonene. The components 1,3,6-Heptatriene and 2,5,5-trimethyl- were highly dominant in the CO2 sample (33.71%), indicating their key role in the compound profile. β -Ocimene was present in high amounts in the CO3, CO4, and CO5 samples, contributing to the aromatic profile and therapeutic properties. Furthermore, sesquiterpene such as caryophyllene were

present in high relative abundance in the CO5 sample (36.02%) and were also identified in all samples. Additionally, other hydrocarbon compounds such as humulene, germacrene D, copaene, and muurolene contributed to the aroma and possibly some biological activity.

Based on Table 3, hydrocarbons represent the predominant chemical class in camphor oil, comprising 34 identified constituents, followed by alcohols [15] and ketones [10]. Among the five samples analyzed, CO1 showed the highest chemical diversity (33 compounds), while CO2 had the fewest [21], though it presented a high relative abundance in specific compound categories. Hydrocarbons were predominant across all samples.

The alcohol compounds were predominated by monoterpenols, which have a distinct aromatic profile and exhibit antioxidant, antimicrobial, and neuroactive properties. Terpineol was identified at elevated levels in CO2 (16.55%) and CO3 (10.40%), although it was present in all samples (Table 2). Other alcohols, including menthol, borneol, isoborneol, (-)-pinanediol, and caryophyllenyl alcohol, were also identified. The CO4 and CO5 samples also contained moderate concentrations of caryophyllenyl alcohol, enriching the oxygenated compound profile. Table 3 shows that the alcohol group makes a significant contribution, especially to CO3 (29.28%) and CO2 (23.34%).

Based on Table 2, the ketone group was identified as consisting of eight compounds, including camphor [(+)-2-Bornanone], verbenone, and d-carvone. Among these, camphor compounds were dominant in sample CO1 (5.41% of 12.01% of the total area of the ketone group) and were also present in samples CO2, CO4, and CO5 (Table 3). These ketone compounds contribute to the aromas of mint, camphor, and spices, and exhibit bioactivities such as antimicrobial and respiratory stimulant properties.

Although not the predominant group, oxide compounds constituted a notable fraction of the phytochemical composition of CO1 (23.28%) and CO2 (9.80%) but were not detected in CO3 and CO4. Caryophyllene oxide, a key compound, contributes to herbaceous scent profiles and antifungal and insecticidal properties [25]. In addition, aldehydes, such as neral dimethyl acetal and α -campholenal, were detected in low concentrations, with the highest levels identified in CO1 (5.83%).

Ether compounds, such as 1,8-cineole (eucalyptol), were found in CO1 (5.25%) and CO3 (0.06%), while esters like bornyl acetate and fenchyl acetate occurred consistently in all samples, with the highest concentration observed in CO1 (6.19%). Carboxylic acids were primarily detected in CO1 (20.79%), with palmitic acid (14.92%) associated with anti-inflammatory and antioxidant activities [26,27]. Overall, CO1 displayed a more complex and compositionally balanced chemical profile, whereas CO5 and CO4 were hydrocarbon-rich, indicating a more intense, and aromatic-dominant volatile composition. Despite originating from a relatively homogenous forest stand, inter-sample variability in phytochemical content is likely attributed to differences in secondary metabolism, influenced by genetic variation, the physiological status of individual trees, and site-specific microhabitat conditions [28–30].

Phytochemical screening via GC-MS of aqueous camphor oleoresin from five individual trees identified 11 major constituents: camphene, (+)-2-bornanone (camphor), borneol, methyl cinnamate, caryophyllene, trans-cinnamic acid, cyclohexane, 1-ethenyl-1-methyl-2-(1-methyl), caryophyllenyl alcohol, (E)-9-octadecene, onocerin, and 28-norolean-17-en-3-one (see Figure 3).

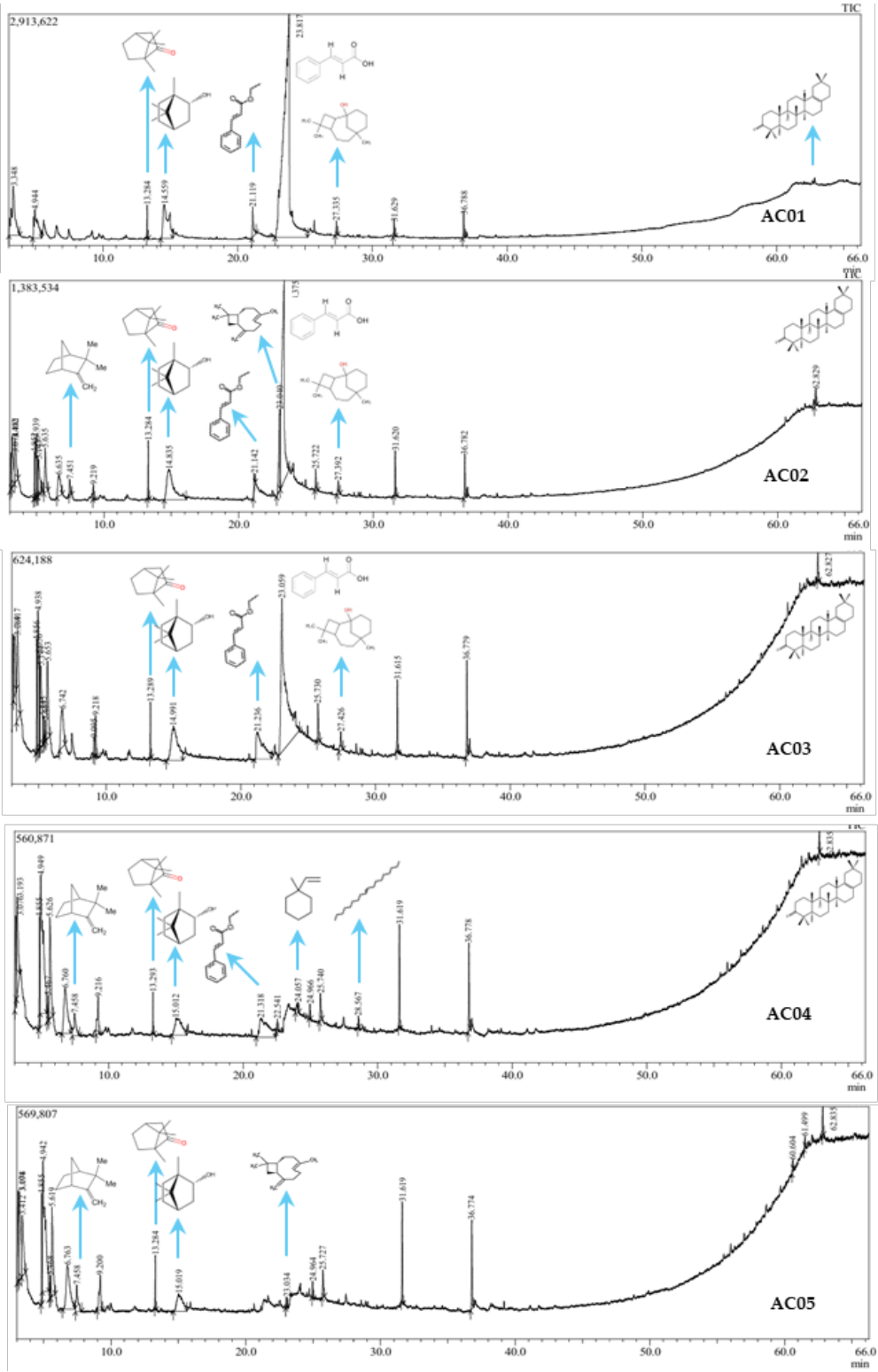


Figure 3. GC-MS of aqueous camphor.

Table 4 presents the volatile compound profile, which comprises five main groups: hydrocarbons, alcohols, ketones, esters, and carboxylic acids, with varying compositions among samples. These differences reflect the dynamics of secondary metabolism influenced by genetic and microenvironmental factors in each tree.

Table 2. Phytochemical content of Sumatra camphor oil.

No	RTime	Component	Group	Area content (%)				
				CO1	CO2	CO3	CO4	CO5
1	7.015	α -Pinene	Hydrocarbon	2.52	-	-	-	-
2	7.186	1,3,6-Heptatriene, 2,5,5-trimethyl-	Hydrocarbon	-	33.71	1.28	3.19	3.74
3	7.325	β -Ocimene	Hydrocarbon	-	-	11.76	7.82	10.46
4	7.385	1,4-Cyclohexadiene, 3,3,6,6-tetramethyl	Hydrocarbon	-	-	-	-	5.78
5	7.390	8-Methylenebicyclo [4.2.0]oct-2-ene	Hydrocarbon	-	-	-	5.26	-
6	7.520	6-Propenylbicyclo [3.1.0]hexan-2-one	Ketone	-	-	4.04	-	-
7	7.537	Camphene	Hydrocarbon	-	1.92	1.59	2.89	1.31
8	8.309	β -Pinene	Hydrocarbon	-	3.41	-	1.49	-
9	8.493	Bicyclo [2.2.1]heptane, 2,2-dimethyl-3-methyl	Hydrocarbon	-	-	4.54	-	5.53
10	8.504	Cyclohexane, 1-isopropyl-1-methyl-	Hydrocarbon	-	-	-	0.31	-
11	8.643	Cyclohexane, 1-methyl-4-(1-methylethyl)-, cis	Hydrocarbon	-	-	1.32	-	-
12	8.759	Bicyclo [4.1.0]heptane, 3,7,7-trimethyl-	Hydrocarbon	-	-	0.49	-	-
13	8.893	β -Myrcene	Hydrocarbon	-	-	0.14	-	0.13
14	9.174	4,7-Methano-1H-indene, 2,4,5,6,7,7a-hexahy	Hydrocarbon	-	0.16	-	-	-
15	9.236	α -Thujene	Hydrocarbon	-	-	0.68	0.64	0.68
16	9.515	Eucalyptol	Ether	0.99	-	0.06	0.54	-
17	9.646	2-Carene	Hydrocarbon	-	-	-	-	0.58
18	9.718	Cymene	Hydrocarbon	1.08	1.08	-	0.80	0.48
19	10.036	D-Limonene	Hydrocarbon	-	4.43	-	-	1.00
20	10.135	para-Menthadiene	Hydrocarbon	-	-	-	-	4.88
21	10.162	1,5-Cyclodecadiene, (E,Z)-	hydrocarbon	-	-	11.80	4.35	-
22	10.330	trans- β -Ocimene	Hydrocarbon	-	0.07	-	-	-
23	11.008	γ -Terpinene	Hydrocarbon	-	-	0.64	0.55	0.46
24	11.298	Terpineol	Alcohol	7.70	16.55	10.40	7.13	3.65

25	11.567	D-Fenchone	Ketone	0.18	-	0.13	-	0.09
26	11.793	p-(1-Propenyl)-toluene	Hydrocarbon	0.43	0.11	-	-	-
27	12.062	α -Phellandrene	Hydrocarbon	-	-	1.35	1.36	-
28	12.667	Neral dimethyl acetal	Aldehyde	3.97	0.88	-	-	-
29	12.831	α -Campholenal	Aldehyde	-	0.24	-	-	-
30	13.394	(+)-2-Bornanone (camphor)	Ketone	5.41	1.00	-	1.26	1.31
31	13.570	Menthol	Alcohol	-	-	2.46	-	-
32	13.710	Linalool	Alcohol	-	0.14	-	-	-
33	13.756	Octanal, 7-hydroxy-3,7-dimethyl-	Aldehyde	-	-	-	-	0.42
34	13.798	Borneol	Alcohol	-	6.39	-	0.82	3.41
35	13.836	Cyclohexanemethanol, α , α ,4-trimet	Alcohol	-	-	2.35	-	-
36	13.940	7-Octen-2-ol, 2,6-dimethyl-	Alcohol	0.78	-	-	-	-
37	14.805	Fenchyl acetate	Ester	0.60	-	-	-	-
38	15.055	Bicyclo [3.1.1]hept-2-ene-2-carboxaldehyde, 6	Aldehyde	1.86	-	-	-	-
39	15.138	Bicyclo [3.1.0]hexan-3-ol, 4-methyl-1-(1-meth	Alcohol	-	-	12.84	-	-
40	15.647	Verbenone	Ketone	3.70	-	-	-	-
41	16.688	D-Carvone	Ketone	0.75	-	-	-	-
42	17.325	(-)-Pinanediol	Alcohol	0.83	0.10	-	-	-
43	18.508	Bornyl acetate	Ester	4.01	1.47	0.12	0.53	0.13
44	18.590	Carvenone	Ketone	0.28	-	-	-	-
45	18.868	Isoborneol	Alcohol	0.49	-	-	-	-
46	21.478	Isobornyl propionate	Ester	0.42	-	-	-	-
47	22.026	Copaene	Hydrocarbon	-	-	-	4.11	-
48	23.300	Caryophyllene	Hydrocarbon	1.29	13.64	18.11	17.30	36.02
49	23.329	2-Heptanone, 7,7-dimethoxy-5-(1-methylethy	Ketone	0.39	-	-	-	-
50	24.194	Humulene	Hydrocarbon	-	4.45	6.59	-	11.96
51	24.297	Propanoic acid, 2-methyl-, 1,7,7-trimethylbicy	Carboxylic acid	0.68	-	0.13	-	-
52	24.531	Cyclohexene, 4-[(1E)-1,5-dimethyl-1,4-hexad	Hydrocarbon	-	-	-	6.70	-

53	24.932	(3R,4aS,5R)-4a,5-Dimethyl-3-(prop-1-en-2-yl	Hydrocarbon	-	-	-	0.25	-
54	25.163	Germacrene D	Hydrocarbon	-	-	-	-	0.69
55	25.532	Bicyclo [5.2.0]nonane, 2-methylene-4,8,8- trimethylnonane bicyclic	Hydrocarbon	-	-	-	-	0.26
56	25.589	Muurolene	Hydrocarbon	-	-	-	0.19	0.16
57	25.920	1H-Cycloprop[e]azulene, decahydro-1,1,7-tri	Hydrocarbon	-	-	-	0.12	-
58	26.277	1-Isopropyl-4,7-dimethyl-1,2,3,5,6,8a-hexahy	Hydrocarbon	-	-	-	0.88	0.48
59	26.700	2,5,9-Trimethylcycloundeca-4,8-dienone	Ketone	0.44	-	-	-	-
60	27.035	2-Naphthalenemethanol, 1,2,3,4,4a,5,6,8a-oct	Alcohol	-	-	-	0.21	0.15
61	27.326	Bornyl isovalerate	Ester	-	-	0.23	-	-
62	27.553	Caryophyllenyl alcohol	Alcohol	-	-	1.23	3.30	2.65
63	27.835	Caryophyllene oxide	Oxide	21.27	8.45	-	-	0.30
64	28.331	3,7-Cycloundecadien-1-ol, 1,5,5,8-tetramethyl-	Alcohol	-	-	-	0.34	-
65	28.361	Terpene oxide	Oxide	-	1.35	-	-	-
66	28.364	Ledol	Alcohol	-	-	-	-	0.62
67	28.428	(1R,3E,7E,11R)-1,5,5,8-Tetramethyl-12-oxab	Ether	4.26	-	-	-	-
68	28.900	Bicyclo [3.1.0]hexane-6-methanol, 2-hydroxy-	Alcohol	-	0.16	-	-	-
69	28.900	2(1H)-Naphthalenone, octahydro-1,1,4a-trime	Ketone	-	-	0.28	-	-
70	29.970	11-Hexadecyn-1-ol	Alcohol	1.49	-	-	-	-
71	31.247	7-Oxabicyclo [4.1.0]heptane, 1-methyl-4-(2-m	Oxide	2.01	-	-	-	-
72	32.135	(1R,2S,4S,5R,7R)-5-isopropyl-1-methyl-3,8-d	Hydrocarbon	0.40	-	-	-	-
73	33.220	9-Undecenal, 2,10-dimethyl-	Aldehyde	-	-	0.14	-	-
74	34.713	3-Carene, 2-acetyl-	Ketone	0.86	-	-	-	-
75	36.841	Methyl palmitate	Ester	0.56	-	-	-	-
76	38.440	n-Hexadecanoic acid	Carboxylic acid	14.92	-	-	-	-
77	40.383	Eicosanoic acid	Carboxylic acid	1.14	-	-	-	-
78	41.680	Methyl stearate	Ester	0.60	-	-	-	-
79	42.733	Octadecanoic acid	Carboxylic acid	4.05	-	-	-	-

Table 3. Summary of phytochemical content of camphor oil.

Group	Number of Component	Sample CO1		Sample CO2		Sample CO3		Sample CO4		Sample CO5	
		n	%	n	%	n	%	n	%	n	%
Hydrocarbon	34	5	5.72	10	62.98	13	60.29	18	58.21	18	84.60
Alcohol	15	5	11.29	5	23.34	5	29.28	5	11.8	5	10.48
Aldehyde	5	2	5.83	2	1.12	1	0.14	-	-	1	0.42
Ketone	10	8	12.01	1	1.00	3	4.45	1	1.26	2	1.40
Ether	2	2	5.25	-	-	1	0.06	1	0.54	-	-
Oxide	3	2	23.28	2	9.80	-	-	-	-	1	0.30
Ester	6	5	6.19	1	1.47	2	0.35	1	0.53	1	0.13
Carboxylic acid	4	4	20.79	-	-	1	0.13	-	-	-	-
Grand Total	79	33		21		26		26		28	

Table 4. The chemical composition and area content of aqueous camphor.

No	R. Time	Component	Group	Area content (%)				
				AC1	AC2	AC3	AC4	AC5
1	7.451	Camphene	Hydrocarbon	-	1.77	-	13.77	22.67
2	13.284	(+)-2-Bornanone (Camphor)	Ketone	1.13	3.58	2.61	5.40	13.67
3	14.835	Borneol	Alcohol	11.18	21.87	18.52	29.52	44.80
4	21.119	Methyl cinnamate	Ester	1.99	1.80	15.38	41.97	-
5	23.034	Caryophyllene	Hydrocarbon	-	11.47	-	-	3.27
6	23.059	trans-Cinnamic acid	Carboxylic acid	85.07	56.51	59.76	-	-
7	24.057	Cyclohexane, 1-ethenyl-1-methyl-2-(1-methyl	Hydrocarbon	-	-	-	3.58	-
8	27.335	Caryophyllenyl alcohol	Alcohol	0.63	1.43	1.91	-	-
9	28.567	9-Octadecene, (E)-	Hydrocarbon	-	-	-	1.57	-
10	60.604	Onocerin	Ketone	3.07	-	-	-	-
11	61.499	28-Norolean-17-en-3-one	Ketone	12.53	1.58	1.83	4.19	-

Cinnamic acid, a carboxylic acid compound, was the predominant constituent in AC1 (85.07%), AC2 (56.51%), and AW3 (59.76%). This aromatic phenolic acid exhibits antioxidant, anti-inflammatory, and anti-microbial activities. However, this compound was absent in AC4 and AC5, indicating variations in secondary metabolic production among the tree samples. Borneol, a monoterpenoid alcohol was consistently abundant across all aqueous camphor samples, particularly in AC5 (44.80%) and AC4 (29.52%). This component is characterized by a distinctive camphor-like aroma and is reported to exhibit antibacterial, analgesic, and sedative properties.

Camphene, a hydrocarbon compound, were identified in considerable concentrations in AC4 (13.77%) and AC5 (22.67%), exhibiting fresh olfactory profiles and insect-repellent properties. Furthermore, caryophyllene, a sesquiterpene, was detected in AC2 (11.47%) and AC5 (3.27%), This compound contributes its analgesic and anti-inflammatory properties. Other hydrocarbons, such as 9-octadecene (E) and cyclohexane derivatives, were observed in AC4, contributed to the volatile complexity of the samples.

Three main ketones were detected: (+)-2-bornanone (camphor), onocerin, and 28-norolean-17-en-3-one. Camphor concentrations exhibited elevated levels in AC5 (13.67%), acting as an antiseptic and respiratory stimulant. 28-Norolean-17-en-3-one, a triterpenoid compound, was predominant in CW1 (12.53%) but minimal in the other samples, indicating that AC1 possesses distinctive chemical characteristics with strong biological activity.

Methyl cinnamate, an ester of cinnamic acid, showed a marked increase in AC3 (15.38%) and was the highest in AC4 (41.97%). This compound is known to impart a sweet and floral aroma and exhibit antioxidant and antimicrobial properties. Caryophyllenyl alcohol, an alcohol derivative of caryophyllene, was recorded in minor quantities in AC1 to AC3, but was not detected in AC4 and AC5.

Overall, each sample exhibited a distinctive chemical profile, depending on the concentration of key compounds, including trans-cinnamic acid, borneol, methyl cinnamate, and camphene. AC1 presents high potential for pharmaceutical applications, AC4 and AC5 are potentially effective for aromatherapy products or natural cosmetics. In contrast, AC2 and AC3 provide a favourable balance between biological activity and aroma quality.

Table 5 shows the differences between camphor oil and liquid camphor, especially regarding compound composition and solubility based on polarity. Non-polar hydrocarbon compounds dominated camphor oil, particularly in sample CO5 (84.60%), followed by CO2 (62.98%), CO3 (60.29%), and CO4 (58.21%). In contrast, the hydrocarbon content in aqueous camphor was very low or absent, except in AC4 (18.92%) and AC5 (25.94%). Alcohol compounds, which exhibit higher polarity, were identified in high concentrations in both fractions, but were more stable and predominant in aqueous camphor, particularly in AC5 (44.80%). This indicates that alcohol has a prominent contribution to the composition of the aqueous fraction, potentially functioning as a bioactive component with antiseptic or aromatic properties, thereby providing an added advantage to this non-timber forest products.

Table 5. Summary of the phytochemical component group and area content.

Group	Area content (%)									
	Camphor oil					Aqueous camphor				
	CO1	CO2	CO3	CO4	CO5	AC1	AC2	AC3	AC4	AC5
Hydrocarbon	5.72	62.98	60.29	58.21	84.60	-	13.24	-	18.92	25.94
Alcohol	11.29	23.34	29.28	11.8	10.48	11.81	23.30	20.43	29.52	44.80
Aldehyde	5.83	1.12	0.14	-	0.42	-	-	-	-	-
Ketone	12.01	1.00	4.45	1.26	1.40	1.13	5.16	4.44	9.59	29.27
Ether	5.25	-	0.06	0.54	-	-	-	-	-	-
Oxide	23.28	9.80	-	-	0.30	-	-	-	-	-

Ester	6.19	1.47	0.35	0.53	0.13	1.99	1.80	15.38	41.97	-
Carboxylic acid	20.79	-	0.13	-	-	85.07	56.51	59.76	-	-

Other polar compounds, such as ketones, esters, and carboxylic acids, are more abundant in aqueous camphor. Esters reach their highest concentration in AC4 (41.97%). Carboxylic acids, especially trans-cinnamic acid, are the predominant compounds in AC1–AC3 at over 50%. This indicates that carboxylic acids are highly polar and readily dissolve in water. High acid content can affect acidic properties and chemical reactivity. This may provide antiseptic, anti-inflammatory, and preservative activities. In industrial applications, carboxylic acids serve as raw materials for pharmaceuticals, food, and cosmetics [31,32].

Esters influence aroma and potential applications [9,10]. Semi-polar oxides and ethers, stable in oil, appear mainly in camphor oil—CO1 (23.28%) and CO2 (9.80%). Aldehydes are typically found in oil, reflecting their tendency to degrade or oxidize in the presence of water. These compounds contribute to a distinctive aroma and pharmacological activity [33,34].

In general, camphor oil contains non-polar volatile compounds with intense aromatic and bioactive properties, while aqueous camphor is more abundant in polar compounds, such as carboxylic acids, esters, and alcohols, with pharmacological and functional potential. Alcohols, due to their polar characteristic, are more soluble in water and contribute to the aroma profile and antimicrobial activity observed in the aqueous fraction. Serving as solvents and active agents, alcohols enhance the overall functional value of the aqueous camphor. This distinction helps determine how each fraction can be used in flavour, fragrance, cosmetics, medicine, or aromatherapy.

Table 6 shows that camphor oil and aqueous camphor have characteristic plant aromas: herbal/woody (pinene, camphene, thujene, borneol, caryophyllene); citrus/fruity (D-limonene, γ -terpinene, methyl cinnamate); camphor/fresh (eucalyptol, camphor, borneol); and sweet/balsamic (methyl cinnamate, cinnamic acid, bornyl acetate). This aroma profile makes camphor oleoresin suitable for aromatherapy, perfumes, cosmetics, and natural flavourings.

Table 6. Aromatic and bioactivity profiles of some of major phytochemical compounds in camphor oleoresin.

Compound	Aroma Profile	Bioactivity	Application			
			Flavour	Fragrance	Cosmetic	Medicine
Pinene	Piney, resinous, herbal	Anti-inflammatory, bronchodilator, AChE inhibitor, GABA modulator, antimicrobial (solvent, biofuel)[35,36]	√	√	√	√
β -Ocimene	Sweet, fruity, herbaceous, floral	Antifungal, anti-inflammatory, plant defense [37,38]	√	√	√	√
Camphene	Herbal, woody, fir, camphor	Antibacterial, antifungal, anticancer, antioxidant, antiparasitic, antidiabetic, anti-inflammatory, anti-leishmanial,	√	√	√	-

		hepatoprotective, antiviral, anti-acetylcholinesterase inhibitory and hypolipidemic activities [38–40]				
β-Myrcene	Fruity, herbal, musky, earthy	Anti-inflammatory, analgesic, sedative, anti-cancer, antitumor [41,42].	-	√	-	-
α-Thujene	woody, herbal, spicy	Antioxidant, antimalarial, antibacterial, antimicrobial [43,44]	-	√	√	√
Eucalyptol	fresh, camphor, spicy	Anti-inflammatory, expectorant, antimicrobial, antiseptic, insecticidal [45–49]	√	√	√	√
D-Limonene	citrusy, sweet	Antioxidant, anti-inflammatory, anticancer, antibacterial, and natural solvent of topical drugs [50,51]	√	√	√	√
γ-Terpinene	Herbal, citrus, spicy, fresh	Antimicrobial, antiparasitic, anticancer, antinociceptive, antiplatelet, natural preservative [52,53]	-	√	√	-
Terpineol	Floral, fresh, pine, citrusy	Antioxidant, antiproliferative [54,55]	√	√	√	√
α-Phellandrene	Peppery, herbal, citrusy, minty	Antifungal, immunostimulant [56–58]	√	√	√	-
Borneol	Soft, woody, balsamic camphor.	anti-inflammatory, analgesic, antibacterial, antiviral, relieves pain and fever, repellent [59]	√	√	√	√

(+)-2-Bornanone (camphor)	Sharp, refreshing, minty camphor	anti-inflammatory, antiseptic, topical analgesic, rubefacient - improves blood circulation [14,16,17]	-	√	√	√
Verbenone	verbena, rosemary-like	Beetle pheromone/inhibitor, anti-microbial [60,61]	-	√	-	√
Bornyl acetate	Balsamic, resin-like, sweet	Anti-inflammatory, immune modulator [62,63].	√	√	-	√
Copaene	Balsamic, woody, peppery, herbal	Insect-repellent, attracts/repels certain pests [64,65].	√	√	-	-
β-Caryophyllene	Woody, spicy, dry	anti-inflammatory, anticancer, analgesic, interaction with CB2 (cannabinoid) receptors, [66,67]	-	√	√	√
Humulene	earthy, woody, slightly spicy	anti-inflammatory, anticancer, antibacterial, [68,69]	-	√	-	-
Cinnamic acid	Sweet, balsamic, cinnamon-like	anti-inflammatory, anticancer, antibacterial, antidiabetic, sunscreen and skin lightening product [70–72]	√	-	√	√
Caryophyllenyl alcohol	Woody, slightly floral	anti-inflammatory, antimicrobial, sedative effects [73]	-	√	-	√
Caryophyllene oxide	Woody, spicy, fresh	antioxidant, anticancer, antifungal [25,74]	-	√	-	√
Methyl cinnamate	Sweet, fruity, like strawberries	anti-inflammatory, antifungal, antimicrobial [75]	√	√	√	-

n-Hexadecanoic acid	Waxy, faint (olive oil-like)	anti-inflammatory, prostaglandin E2 9 reductase inhibitor [76–78]	-	-	√	-
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Most compounds in Table 6 exhibit biological activities, particularly anti-inflammatory, antimicrobial, antifungal, and antioxidant properties. Anti-inflammatory properties are the predominant activity, possessed by almost all the main compounds, including pinene, ocimene, camphene, myrcene, borneol, camphor, D-limonene, terpineol, caryophyllene, cinnamic acid, and bornyl acetate. These compounds, known for their refreshing aromas and analgesic, transdermal absorption effects, are highly relevant for developing topical products (ointments, balms), herbal supplements, or natural pain relief therapies [10,14,16,35,36,38,41,42,50,55,63,67,71,79,80].

In the flavour industry, compounds such as D-Limonene, methyl cinnamate, pinene, and eucalyptol provide citrus, sweet, herbal, fruity, and refreshing aromas [50,75,81–86]., enhancing food aroma profile. Terpineol, ocimene, camphor, borneol, eucalyptol, camphene, caryophyllene oxide, methyl cinnamate, cinnamic acid, and ocimene exhibit antimicrobial and antifungal properties [25,38,46,72,75], which can extend the shelf life of food products.

In the cosmetics industry, compounds such as α -thujene, bornyl acetate, and cinnamic acid offer antioxidant, brightening, and antimicrobial benefits. These compounds present potential as natural alternatives to synthetic preservatives in cosmetics and personal care products. Compounds such as camphor, borneol, cinnamyl cinnamate, and caryophyllene oxide provide distinctive, intense aromas—ranging from woody to balsamic—and function as fixatives to extend the longevity of perfumes [14,16,25,87,88]. Terpineol, camphene, limonene, thujene, and humulene exhibit antioxidant properties by scavenge free radicals. These compounds are suitable for anti-aging, skincare, and natural UV protection formulations.

One compound that stands out is cinnamic acid, notable for its applications and therapeutic potential. Specifically, cinnamic acid is an aromatic compound with a mild, sweet, and balsamic aroma profile. It is used in flavourings for its ability to add depth to the sweet-spicy flavours, and in cosmetics as an active agent for skin lightening and UV protection [89]. In medicine, cinnamic acid exhibits various important biological activities, including anti-inflammatory, antimicrobial, anticancer, antidiabetic, and antioxidant properties [70,71]. Furthermore, pharmacological studies have demonstrated that cinnamic acid derivatives can inhibit pro-inflammatory enzymes and induce apoptosis in cancer cells, rendering them a potential source for the development of natural compound-based drugs. Other compounds, such as β -caryophyllene, exhibit further therapeutic potential by interacting with CB2 receptors in the endocannabinoid system, opening opportunities for neuroprotective or pain-relieving applications [25,67]. Thus, beyond their pleasant aroma, these biological activities make these aromatic compounds not only additives but also functional components in various consumer products.

3. Materials and Methods

3.1. Materials

Two grades of oleoresin, aqueous and camphor oil, were harvested from each of five sample trees by tapping the trunk to break the resin channels, allowing the oleoresin to exude. The sample Sumatra camphor trees grew naturally in a lowland tropical forest area located in the Sibagindar Village forest (2°30'53"N 98°09'05"E), Pakpak Bharat Regency, North Sumatra Province. This area was the hinterland of the port cities of Barus and Singkil in the past. Currently, this natural forest is the only remaining endemic habitat of the camphor species in Sumatra. The sample trees had a diameter of about 50 cm and a total height of 30-40 meters.

3.1. Methods

3.1.1. Sample Collection

Oleoresin collection is carried out following traditional harvesting practices by local communities in Pakpak Bharat, North Sumatra. First, to obtain the oil fraction, a 10 cm deep notch is made at the base of the tree (100-130 cm above ground or 20 cm above the buttress). As a result, a slow-flowing balsam liquid will exude from the notch. Next, aqueous camphor is obtained through a shallower V-shaped incision (3-5 cm deep) made at a height of 100-130 cm above ground, and a horizontal cut at a height of 3-5 meters of the same depth, orthogonal to the base incision point (Figure 4). All oleoresin is collected, and the time from completion of tapping until the last drop flows is recorded. The viscosity of each sample, both aqueous camphor (5 samples) and camphor oil (5 samples), was measured using a Brookfield DV2T Viscometer.

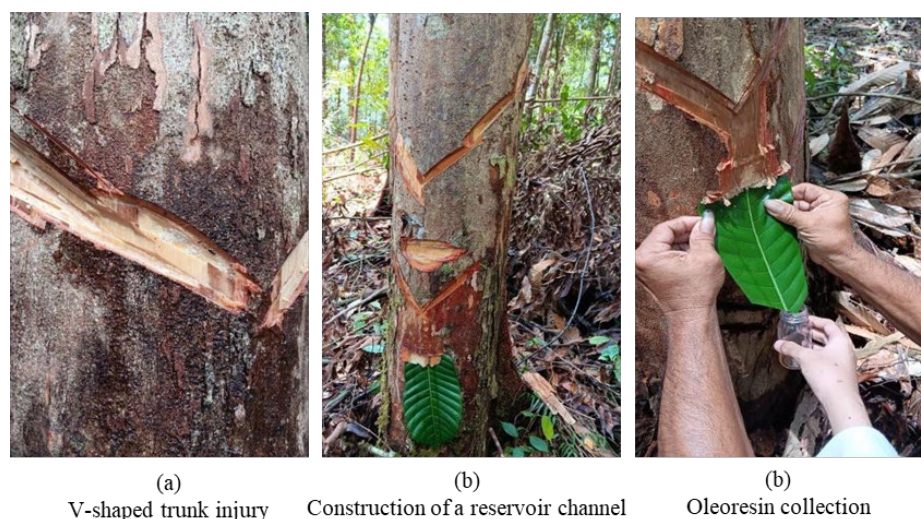


Figure 4. Oleoresin tapping of Sumatra camphor oleoresin.

3.2. Analysis Methods

Gas chromatography-mass spectrometry was used to identify Sumatra oleoresin components (aqueous and oil fraction) in the injected samples. The obtained samples were then identified for their phytochemical compounds using a Shimadzu GC-MS-QP2010 Ultra device at the Integrated Laboratory for Bioproducts (i-Lab) BRIN in Cibinong, West Java Indonesia. Since the target compound is an aromatic compound, the column used was Rtx-1 (30m x 0.25mm, thickness 0.25um), with a column temperature of 40-250°C, a temperature rise rate of 4°C/min, a detector temperature of 285°C with a carrier gas of nitrogen at a column rate of 1.78 mL/min and a flow rate of 3.0 mL/min. Identification of phytochemical compounds was carried out by searching the standard spectrum library and the NIST literature. The area of content percentage of each component was calculated using the peak area normalization method.

4. Conclusions

This research identified 79 bioactive compounds in camphor oil and 11 in aqueous camphor. Both have distinct, valuable chemical profiles with broad aromatherapeutic and biological potential. Camphor oil is characterized by non-polar volatile compounds— apart from sample CO1, which exhibits a more balanced compound profile, with notable aroma and bioactivity. In contrast, aqueous camphor emphasizes polar compounds, including carboxylic acids, esters, and alcohols, that offer pharmacological and functional benefits. These findings highlight opportunities for developing natural products in areas such as flavour, fragrance, cosmetics, and medicine, as well as topical applications.

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