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Content and Chemical Composition of Essential Oil from Cardamom (*Elettaria cardamomum* (L.) Maton)

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Abstract: This study was conducted to determine and compare the essential oil content and composition of eight samples of cardamom (*Elettaria cardamomum*). The yield of essential oils isolated by hydrodistillation from the dried fruits varied from 4 to 56 mL kg^{-1}. Chemical analysis by gas chromatography coupled with mass spectrometry (GC/MS) revealed the presence of 21–48 compounds accounting for 98.88–99.98 % of the total essential oils. Alpha-terpinyl acetate was the most abundant compound in all samples (35.99–62.28 %), followed by 1,8-cineole (0.24–30.62 %), α-terpineol (2.18–16.75 %), linalool (0.81–7.25 %), and linalyl acetate (1.49–4.67 %). The radar plots easily distinguished cardamom samples. Multivariate principal component analysis (PCA) was used to evaluate the phytochemical diversity of the cardamom fruits. The results presented provide a first insight into the substantial differences in the yield and composition of the essential oil of commercially available cardamom fruits and underline the superior quality of the whole fruit compared to the powdered form.

Keywords: *Elettaria cardamomum*, cardamom, essential oils, GC/MS, α-terpinyl acetate, 1,8-cineole, principal component analysis.

INTRODUCTION

Elettaria cardamomum (L.) Maton (cardamom) is a herbaceous perennial plant of the Zingiberaceae family, prized for its fruits, which are used both as a culinary spice and for medicinal purposes. This aromatic plant is native to South India and Sri Lanka, from where it has spread to other tropical countries. Guatemala is now the world´s leading producer and exporter of cardamom, followed by India and Tanzania. Several cultivars have been described and cultivated.[1] The ripe fruits are harvested by hand-picking, and the main harvest time is between October and November. The limited cultivation area and the labour-intensive harvest are the main reasons why cardamom is one of the most expensive spices in the world, after saffron and vanilla.[2]

The cardamom fruits are dark green, ovoid or oblong, trilocular capsules containing around 15–20 aromatic, reddish-brown seeds. Postharvest processes include washing and drying fruits. This is the most important part of processing and should be done as quickly and briefly as possible to avoid loss of flavour and green colour.[2] Dried cardamom fruits are available on the market mainly in whole form or as ground powder, but also as decorticated seed, essential oil, and oleoresin.[3] Cardamom is a valued spice that has been known since ancient times and is used in the preparation of food, confectionery, meat, bakery, and dairy products, teas, and beverages due to its distinctive aroma and flavour.[4] The pharmaceutical, perfume, and cosmetic industries also make extensive use of these plant products.[3] Most importantly, cardamom fruit is a popular herbal drug that is used extensively in traditional Asian medical systems such as Ayurveda, Unani, and traditional Chinese medicine. It is used to treat various gastrointestinal problems (upset stomach, nausea, vomiting, flatulence, cramps, and gastritis), respiratory conditions (asthma, bronchitis, and cough), and other conditions such as oral diseases, halitosis, colds, flu, urinary tract infections, and depression.[3–5]

Cardamom fruits have been found to possess a wide range of biological and pharmacological activities. Various cardamom extracts and essential oils have shown antimicrobial activity against periodontal pathogens,[6]

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foodborne bacteria, and fungi.[7] The antioxidant[8] and anti-inflammatory properties[6,9] of cardamom have been documented and proposed as mechanisms for its chemopreventive and anticancer properties.[10–12] Cardamom powder consumption has been found to prevent obesity, glucose intolerance, inflammation, and oxidative stress in the liver of high-carbohydrate, high-fat diet induced obese rats.[13] Gastroprotective and antispasmodic *in vivo* effects have also been reported.[14] The positive neurological effects of cardamom, such as neuroprotective, anxiolytic, and antidepressant effects,[15–17] have been demonstrated. Several recent meta-analyses summarize the available evidence from randomized controlled trials and suggest that cardamom intake significantly reduces triglyceride levels,[18] improves glucose metabolism[19] and blood pressure control, and has anti-inflammatory effects,[20] which could help patients with unhealthy metabolic status to better manage their health.

The phytochemical studies carried out so far have shown that the fruits of *E. cardamomum* contain terpenes as components of the essential oil, then polyphenols of the flavonoid and phenolic acid group, as well as fatty acids, phytosterols, and carotenoids.[9,21,22]

Their distinct flavour and aroma, as well as the bioactivity, are mainly due to the essential oil components. Cardamom oil is rich in monoterpenes, of which α-terpinyl acetate and 1,8-cineole are the main constituents ahead of α-terpineol, sabinene, and linalool.[23] Research on essential oils has revealed considerable variability in their chemical composition, depending on several factors such as plant variety,[24] geographical origin of the cardamom fruit,[24] environmental conditions,[25] harvest time[26] and extraction method.[27]

The quality of herbal drugs rich in essential oil is mainly determined by their content and composition, and as already mentioned, can be influenced by many factors along the supply chain. For their medicinal use, quality and quantity assessments of the chemical constituents are very important, as ensuring a consistent quality of the herbal drug is crucial to guarantee its efficacy and safety.[28] The demand for the cardamom fruit, an exotic herbal drug known for its health-promoting properties, is increasing in Europe. However, there are no studies that reveal the bioactive constituents of the cardamom fruits available on the market, nor those that compare the phytochemical profiles of the two most common forms, the whole fruit and the powder. Given the above, the present study aimed to provide an insight into the actual phytochemical profile of commercially available cardamom fruits by analysing the essential oil as the most important quality attribute.

EXPERIMENTAL

Plant Material and Chemicals

A total of 8 batches of cardamom (*E. cardamomum*) fruit samples were purchased from specialized spice and tea stores and organic food stores, as well as from online-shops. The investigated plant material included samples in whole and powdered form, available on the Croatian market, and more detailed information is provided in Table 1. The identity of the plant material was confirmed by macroscopic and microscopic analyses, in accordance with the descriptions provided in the literature.[29] Xylene and *n*-hexane were purchased from Merck (Darmstadt, Germany). All solvents were of GC grade.

Determination of Essential Oil Content

The whole fruit samples were ground into a fine powder immediately before the analysis. Ten grams of the powdered sample was placed in a distillation flask together with 400 mL of distilled water and subjected to hydrodistillation in the Clevenger-type apparatus for 3 hours, according to the method recommended in the European Pharmacopoeia.[30] Essential oil content was estimated as the average of three replications and calculated based on the plant's dry weight (expressed in mL kg^{-1}). The oils were dried over anhydrous sodium sulphate and stored in an amber-coloured vial at 4 °C until further analysis.

Chemical Analysis of the Essential Oils

The chemical composition of the essential oil was analysed using an Agilent 7890B gas chromatograph (Agilent, USA) equipped with a mass detector (Agilent 5977 A). The column

Table 1. List of the studied cardamom fruit samples.

Sample	Plant material form	Sales network	Labelling information	Origin	Batch expiration date
W1	whole	H, O	Cardamom green	Guatemala	09/2024
W2	whole	S	Cardamom	Iran	11/2023
W3	whole	S, O	Cardamom	Guatemala	04/2025
W4	whole	H, O	Cardamom whole bio	Guatemala	09/2023
P1	powdered	H, O	Cardamom powder - green	Guatemala	07/2022
P2	powdered	H, O	Cardamom powder	Guatemala	01/2024
P3	powdered	S, O	Cardamom powder	Guatemala	04/2025
P4	powdered	H, O	Cardamom powder	Guatemala	10/2022

S – specialized spice and tea store; H – specialised organic and healthy food store; O – online shop

used for separation was an HP-5 MS (30 m × 0.25 mm i.d., film thickness: 0.25 µm) with 5 % phenylmethylsiloxane as the stationary phase. The essential oils were diluted in hexane (1 : 100), and 1 µL of the samples was injected into the system. The operating conditions of the GC/MS system were as follows: carrier gas was helium with a flow rate of 1 mL min^{-1}; the split ratio was 1 : 50; injector temperature was 250 °C; the mass spectrometer transfer-line, ion source, and quadrupole temperatures were 280, 230, and 150 °C, respectively; the energy ionization was 70 eV and the mass spectra range was 40–400 amu. The oven temperature was started at 60 °C, held for 1 min, and then increased to 200 °C with a rate of 3 °C min^{-1} and held at this temperature for 10 min. Under the same conditions, a mixture of series *n*-alkanes (C_9–C_{23}) was injected into the GC/MS system to calculate the retention indices.

Identification of Essential Oil Constituents

The identification of essential oil constituents was based on their GC retention index (RI), relative to C_9–C_{23} *n*-alkanes on the HP-5 MS column. The RI was calculated using the Van den Dool & Kratz equation,[31] and then compared with those reported in the literature.[32] Identification was also performed by computer matching of the mass spectra of the peaks with the Wiley 9, NIST14, and HPCH 2205 libraries, as well as by comparison of the MS fragmentation patterns with those reported in the literature.[32] The individual components' concentration (%) is expressed as a percentage of the chromatographic peak area relative to the total area of the essential oil by electronic integration without correction factors. The analysis of the essential oils was the average of triplicate independent analyses.

Statistical Analysis

The results of the phytochemical analyses (triplicated experiments) were presented as mean value ± standard deviation, and significant differences between samples were analysed using the online software astatsa.com. The means of all experiments were subjected to the analysis of variance (ANOVA) and Tukey's post hoc multiple-comparison test, and a *p*-value of 0.05 or less was considered statistically significant. A radar plot analysis was performed using Microsoft Excel 2016. The processed phytochemical data (mean values) were analysed using Minitab statistical software for multivariate data analysis. Principal component analysis (PCA) was used to obtain information on sample grouping, similarities, and differences among the analysed plant material.

RESULTS AND DISCUSSION

The essential oil of *E. cardamomum* was isolated by hydrodistillation, and the average yield of fruit samples

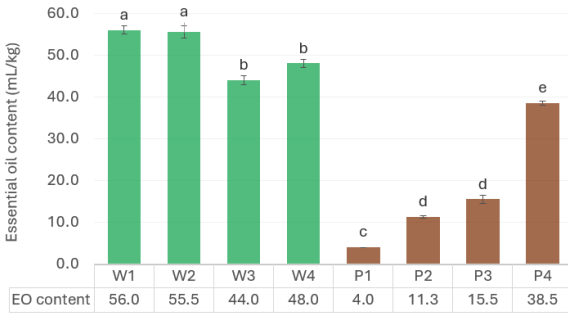

Figure 1. Essential oil content in the *E. cardamomum* samples, including the whole fruit (green) and the powdered form (brown). Values are the means of three replicates. Values marked with different superscript letters are significantly different ($p < 0.05$).

ranged from 4 to 56 mL kg^{-1} (Figure 1). The results confirm previous findings on the high variability of cardamom essential oil content, which ranges from 2 to 87 mL kg^{-1}, depending on variety, plant part, degree of ripeness, and extraction method.[33] The whole fruits contained 44–56 mL of essential oil per kg of fruit, which is equal to or higher than the values previously reported for cardamom from Guatemala.[33,34] Our study showed for the first time that whole cardamom fruits contain significantly ($p < 0.05$) higher amounts of essential oil than the commercially available fruits in powder form. It was also found that the variation in essential oil content (4.0–38.5 mL kg^{-1}) was more pronounced in powdered cardamom. Although the pre-ground plant material is more convenient to use, especially in food, our results clearly showed that it contains a significantly lower amount of volatile bioactive constituents.

The results of the GC/MS analyses of the essential oils isolated from cardamom are listed in Table 2, while Figure 2 shows the representative GC chromatographic profile of the oils. A total of 21–48 volatile components were identified, accounting for 96.88–99.98 % of the total oil composition. The essential oil of cardamom fruits consisted mainly of oxygenated monoterpenes (64.81–93.10 %), followed by monoterpene hydrocarbons (0.20–11.35 %), oxygenated sesquiterpenes (0.81–5.95 %), and sesquiterpene hydrocarbons (0–4.86 %). Of the eight cardamom samples, only one contained a higher amount of other class constituents (22.97 %).

The chemical compositions of the investigated cardamom fruit samples were characterized by the predominance of α-terpinyl acetate (35.99–62.28 %), followed by 1,8-cineole (0.25–30.62 %). Other significant monoterpenes were α-terpineol (2.18–16.75 %), linalool (0.81–7.25 %), and linalyl acetate (1.49–4.67 %) (Table 2).

Table 2. Chemical composition of the essential oils of eight fruit samples of *E. cardamomum*.

No.[a]	RI_{exp}[b]	RI_{lit}[c]	Compound[d]	Relative percentage / %							
				W1	W2	W3	W4	P1	P2	P3	P4
1	926	930	α-Thujene	0.12	0.13	0.11	0.16		0.02		0.12
2	933	939	α-Pinene	0.92	1.01	0.87	1.32		0.03	0.11	0.67
3	973	975	Sabinene	2.90	3.17	3.12	3.76		0.09	0.51	2.12
4	976	979	β-Pinene	0.30	0.32	0.31	0.39		0.04	0.14	0.23
5	988	988	Sulcatone						0.04		
6	991	991	β-Myrcene	1.54	1.62	1.69	1.87		0.26	0.44	1.25
7	1004	999	*n*-Octanal						0.04		
8	1017	1017	α-Terpinene		0.22	0.13			0.15	0.18	0.17
9	1024	1025	*p*-Cymene	0.60	0.10	0.41	0.48		0.08	0.12	0.20
10	1028	1029	Limonene	2.42	2.20	2.75	2.92	0.20	1.18	2.02	1.87
11	1031	1031	1,8-Cineole	29.05	26.92	26.67	30.62	0.25	3.25	11.99	26.25
12	1037	1037	*cis*-β-Ocimene						0.06	0.14	
13	1047	1050	*trans*-β-Ocimene						0.11		
14	1058	1060	γ-Terpinene	0.19	0.45	0.32	0.24		0.28	0.38	0.38
15	1066	1070	*cis*-Sabinene hydrate	0.29	0.38	0.38	0.34		0.30	0.33	0.29
16	1072	1073	*p*-Mentha-3,8-diene						0.11		
17	1088	1089	Terpinolene	0.18	0.24	0.26	0.21		0.37	0.42	0.28
18	1101	1097	Linalool	4.98	5.23	5.25	4.43	0.81	5.50	6.39	7.25
19	1166	1169	Δ-Terpineol						0.31		0.18
20	1177	1177	Terpinen-4-ol	1.83	1.67	1.83	1.61	0.52	1.63	1.94	1.96
21	1190	1189	α-Terpineol	3.03	3.32	3.82	2.63	2.18	5.95	4.61	16.75
22	1219	1217	*trans*-Carveol					0.28	0.09		
23	1241	1238	Neral		0.17	0.40	0.22		0.19		0.18
24	1243	1243	Carvone					0.22	0.24		
25	1256	1257	Linalyl acetate	4.57	4.67	3.37	4.28	1.64	3.94	3.72	1.49
26	1271	1267	Geranial	0.30	0.53	0.67	0.36		0.30		0.24
27	1285	1285	*trans*-Anethole						0.79		
28	1303	1299	Carvacrol					1.31	0.07		
29	1317	1318	*cis*-Dihydro-α-terpinyl acetate	0.17	0.16		0.17		0.27	0.23	0.16
30	1324	1325	Methyl geranate					0.32	0.21		
31	1351	1349	α-Terpinyl acetate	44.66	44.80	45.79	42.35	56.52	60.45	62.28	35.99
32	1361	1359	Eugenol						0.72		
33	1365	1362	Neryl acetate						0.26	0.21	
34	1374	1377	α-Copaene					0.22	0.04		
35	1384	1381	Geranyl acetate	0.72	0.66	0.56	0.85	0.76	0.82	1.40	0.27
36	1391	1391	β-Elemene						0.04		

[a] In the order of elution on HP-5 MS.

[b] RI_{exp}. experimental values of retention indices on HP-5 MS.

[c] RI_{lit}. literature values of retention indices.[32]

[d] Compounds identified based on mass spectra and retention indices.

Table 2. (continued) Chemical composition of the essential oils of eight fruit samples of *E. cardamomum*.

No.[a]	RI_{exp}[b]	RI_{lit}[c]	Compound[d]	Relative percentage / %							
				W1	W2	W3	W4	P1	P2	P3	P4
37	1417	1419	β-Caryophyllene					1.70	0.27	0.19	
38	1432	1437	γ-Elemene						0.02		
39	1483	1490	β-Selinene	0.27	0.24			1.75	0.50	0.27	0.18
40	1492	1498	α-Selinene					0.43	0.16		
41	1512	1514	γ-Cadinene		0.16			0.45	0.36		
42	1521	1523	Δ-Cadinene					0.31	0.10	0.36	
43	1563	1563	*trans*-Nerolidol	0.94	1.29	1.26	0.81	2.42	5.10	1.54	1.42
44	1579	1583	Caryophyllene oxide					0.49	0.36		
45	1793	1809	Ambrial					1.91	0.49		
46	1962	1964	Palmitic acid					0.44	0.17		
47	1979	1994	15,16-Dinorlabda-8(17),11-dien-13-one					1.29	0.35		
48	2125	2135	Coronarin E		0.28			20.77	0.77		
49	2296	2300	Tricosane					0.47			
			Monoterpene hydrocarbons	9.17	9.46	9.97	11.35	0.20	2.78	4.46	7.29
			Oxygenated monoterpenes	89.60	88.51	88.74	87.56	64.81	85.29	93.10	91.01
			Sesquiterpene hydrocarbons	0.27	0.40			4.86	1.49	0.82	0.18
			Oxygenated sesquiterpenes	0.94	1.29	1.26	0.81	4.82	5.95	1.54	1.42
			Others		0.28			22.97	1.37		
			Identified compounds / %	99.98	99.94	99.97	99.72	97.66	96.88	99.92	99.90

[a] In the order of elution on HP-5 MS.
[b] RI_{exp}. experimental values of retention indices on HP-5 MS.
[c] RI_{lit}. literature values of retention indices.[32]
[d] Compounds identified based on mass spectra and retention indices.

The most abundant volatile component among the sesquiterpenes was nerolidol (0.81–5.10 %), followed by ambrial (up to 1.91 %) and β-selinene (up to 1.75 %). Our results provide the first insight into the phytochemical profile of two commonly available forms of *E. cardamomum* fruit. A comparison of the percentage content of identified terpenoids showed significant differences among the cardamom samples. The whole fruits contained 42.35–45.79 % α-terpinyl acetate, 26.67–30.62 % 1,8-cineole, 4.43–5.25 % linalool, and 3.37–4.67 % linalyl acetate, respectively. As evident, the batches of the whole cardamom fruit showed a similar chemical profile characterized by relatively consistent levels of all major compounds, indicating uniform quality. In contrast, a comparison of the chromatographic profile of the essential oil from the cardamom powders revealed considerable qualitative and quantitative differences. Alpha-terpinyl acetate (35.99–62.28 %) was the major volatile component in all four powders analysed. Likewise, significant variation was observed in the concentrations of 1,8-cineole (0.25–26.25%) and α-terpineol (2.18–16.75 %), indicating notable differences in the overall chemical composition of the samples.

Alpha-terpinyl acetate and 1,8-cineole were identified as major constituents in the fruits of *E. cardamomum*,[33] confirming our results. However, considerable differences in their percentage content can be observed. Cardamom purchased from a local market in Saudi Arabia was dominated by 1,8-cineole (55.4 %), while α-terpinyl acetate (28.6 %) was the second most abundant volatile constituent.[35] In contrast, cardamom available at the local Turkish market contained a higher proportion of α-terpinyl acetate (40.7 %) and a lower amount of 1,8-cineole (25.6 %), followed by linalool (6.4 %).[36] These results, which are similar to those of our study, suggest a common origin of the herbal drug samples from Guatemala. A recent comprehensive profiling of 22 cardamom accessions growing in Southern India identified two distinct clusters, one with a higher concentration of α-terpinyl acetate and another with a higher concentration of 1,8-cineole.[23] The essential oil of *E. cardamomum* from Guatemala has previously been

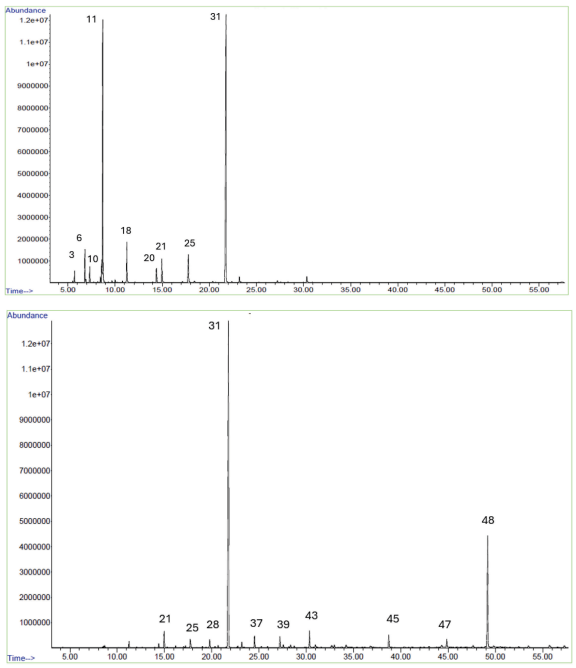

Figure 2. GC/MS chromatographic profile of essential oils isolated from (upper) the whole fruit W1 and (lower) the powdered fruit P1 of *E. cardamomum*. Numbering of components is specified in Table 2., with peak identification of the most abundant constituents.

reported to contain 37.93 % α-terpinyl acetate, 27.89 % 1,8-cineole, 5.62 % sabinene and myrcene, and 3.67 % limonene.[37] According to our study, whole cardamom fruits from Guatemala contained slightly higher levels of α-terpinyl acetate (42.35–45.79 %), but the overall essential oil composition remained relatively consistent, indicating a reliable phytochemical profile for samples from this geographical origin. While geographical origin is known to significantly influence essential oil composition, other factors may also contribute to the observed variability. For example, one study on Guatemalan cardamom reported significantly lower levels of the two dominant constituents, α-terpinyl acetate (18.71 %) and 1,8-cineole (10.59 %).[7] In addition to geographical origin, such differences may arise from genetic variations, environmental conditions, harvest time, and/or extraction methods. Equally less important is the processing of the plant material, especially drying[38] and pulverization,[39] which can significantly influence the composition of cardamom essential oil. Finally, the duration and conditions of storage also have qualitative and quantitative effects on the essential oil,[40,41] which may also partly explain the distinctly different phytochemical profiles of cardamom powder compared to the whole fruit.

It is important to note that the essential oil of one powder sample differed greatly in its composition from the others. Although it was dominated by α-terpinyl acetate (56.52 %), it contained traces of 1,8-cineole (0.25 %) and an unusually high content of coronarin E (20.77 %). This diterpenoid has been found in cardamom fruits before, though rather infrequently and in relatively low amounts.[8] In an earlier study, coronarin E (17.7–34.2 %) was identified as the primary component of the essential oil of *E. cardamomum* leaves.[42] The results obtained suggest that commercially available samples of cardamom fruit may be adulterated with leaves. It is known that powdered herbal drugs are more prone to adulteration than intact plant parts, so their authentication is particularly important to ensure safety and efficacy.

A radar plot analysis was performed to visualize the differences among the *E. cardamomum* fruit samples based on their phytochemical component values. This method enables routine, simple, and rapid discrimination between samples and can serve as an effective tool for assessing the quality of plant material.[43] Figure 3 shows the distribution of essential oil patterns of eight *E. cardamomum* fruit samples, based on the average content of the six most abundant components. The whole and powdered cardamom fruit showed distinctly different characteristic patterns and were easy to distinguish.

The determined quality parameters of the *E. cardamomum* fruits were further evaluated using multivariate statistical PCA to clarify the main phytochemical similarities and differences between the samples. Figure 4 displays the corresponding biplot of PCA based on the correlation matrix. The PCA analysis showed that the first two principal components with eigenvalues greater than 1 explained 80.0 % of the total variability, indicating that they satisfactorily accounted for the variation in the data. The first principal component (PC1) accounted for 53.9 % of the total variance and was characterized by high loadings of essential oil content, 1,8-cineole, α-terpinyl acetate and coronarin E concentrations. The second principal component (PC2) explained 26.1 % of the variability and was characterized by high loadings of α-terpineol and linalyl acetate. The samples in the figure are distributed over different regions of the coordinate system and are clearly separated from each other without overlapping, indicating significant differences in the content and composition of bioactive compounds in cardamom fruits. The PCA divided the samples into four distinct clusters. A clear separation between whole and powdered cardamom samples was observed. Cluster I, which comprises W1, W2, W3, and W4, exhibited the highest contents of essential oil, 1,8-cineole, and linalyl acetate, along with an intermediate content of α-terpinyl acetate. In contrast to the whole fruit samples, which formed a single cluster, the powdered fruit samples were divided into three different clusters. Cluster II, consisting of P2 and P3, showed an intermediate essential oil yield and was characterized by the highest content of

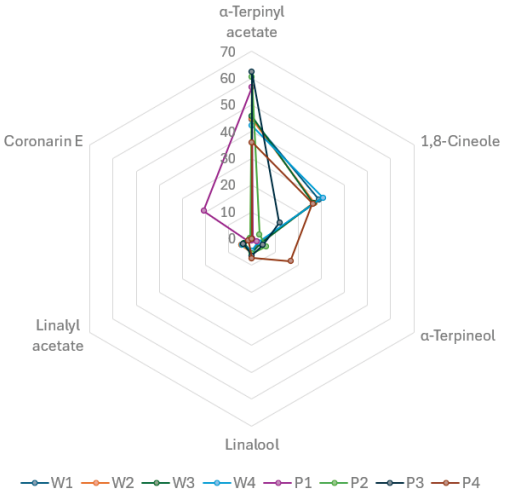

Figure 3. Radar plots showing the differences in *E. cardamomum* fruit quality in terms of percentage content of six most abundant essential oil components. W1–W4 are whole E. cardamomum fruit samples, while P1–P4 are powdered one.

α-terpinyl acetate and the lowest content of 1,8-cineole. Cluster III, which comprised P1, had the lowest essential oil value, with the lowest content of 1,8-cineole and linalool, and the highest content of α-terpinyl acetate and coronarin E. Cluster IV, to which P4 belonged, had a higher yield of essential oil, characterized by the lowest content of α-terpinyl acetate and the highest amounts of 1,8-cineole, α-terpineol, and linalool. Previous reports have illustrated the effectiveness of PCA in discriminating chemical profiles within certain plant species or genera.[44,45] In this study, PCA played an important role in improving our understanding of the quality of *E. cardamomum* fruit samples in terms of essential oil content and composition. The results obtained support the hypothesis that the differences in bioactive compounds between cardamom samples are influenced by the processing methods.

Since the bioactivity of herbal drugs is determined by the content of phytochemicals, the quantification of the chemical marker(s) is crucial for standardizing plant material and ensuring consistent quality, efficacy, and safety. Alpha-terpinyl acetate and 1,8-cineole can be considered as active chemical markers that exhibit a range of biological properties. In addition to its antimicrobial properties, α-terpinyl acetate has demonstrated its multi-target-directed ligand potential in Alzheimer's disease.[46,47] Preclinical studies have shown that 1,8-cineole exhibits anti-inflammatory, antioxidant, antimicrobial, bronchodilator, analgesic, and pro-apoptotic effects.[46,48] Furthermore, the health benefits of 1,8-cineole for patients with respiratory disorders have been demonstrated in numerous clinical trials.[49] Scientific evidence also points to its beneficial role in Alzheimer's disease, where it has been shown to be the component most responsible for the inhibitory effects of *E. cardamomum* essential oil on acetylcholinesterase.[50] Interestingly, the anti-dementia activity has been attributed to a pool of oxygenated terpenes (linalool, linalyl acetate, and α-terpineol) in addition to 1,8-cineole and α-terpinyl acetate, which

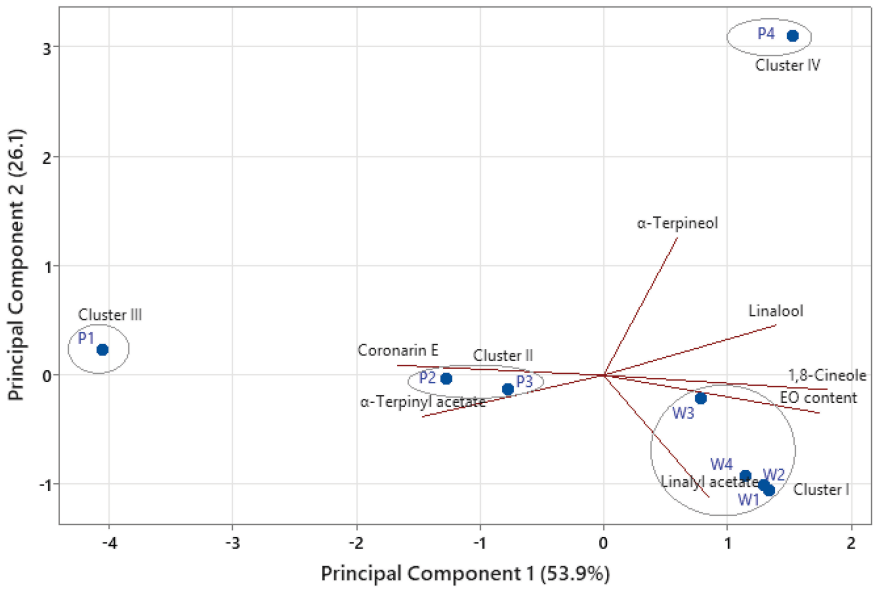

Figure 4. Bi-plot of principal components based on the mean value of cardamom essential oil content and composition. PCA explains 80.0 % of the data variability. W1-W4 are whole *E. cardamomum* fruit samples, while P1-P4 are powdered fruit samples.

synergistically contribute to the overall activity of the essential oil, suggesting that their content and ratio should be considered in future pharmaceutical quality requirements to ensure optimal efficacy. Based on the obtained phytochemical results, which indicate that the essential oil belongs to the terpinyl acetate chemotype, it can be assumed that the analyzed cardamom may have potential applications in phytopreparations aimed at supporting oral health (due to its antimicrobial activity), treating metabolic disorders, and providing neuroprotective effects through its anti-inflammatory and antioxidant properties.[6,12,14,17,19]

Overall, the phytochemical results presented in this study demonstrated substantial variations in the content and composition of bioactive constituents among the analysed samples of *E. cardamomum* fruit, emphasizing the necessity for quality assurance of cardamom before its commercial and medicinal use.

CONCLUSION

The cardamom fruit, a highly aromatic spice prized for its unique flavour, is gaining global recognition for its health-promoting properties. Our findings provide a first insight into the content and composition of bioactive volatiles in the two most commonly commercially available forms of cardamom fruit. Although cardamom powder is often more convenient to use, our study shows that it contains a significantly lower amount of bioactive constituents compared to the whole fruit and has a highly variable phytochemical composition. Comparative phytochemical studies revealed that the whole cardamom fruits available in Croatia are relatively homogeneous in terms of essential oil content and composition, suggesting their superior quality. Considering the significant biomedical potential of cardamom fruits and the growing demand in the European market, it is crucial to continue research to establish pharmaceutical standards that would define the properties and minimum requirements for the quality of raw materials, ensuring consistent quality, biological activity, and safe use.

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