# Phytochemical profiling and evaluation of the biological potential of caraway (Carum carvi L.) essential oil

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**Abstract.** Caraway fruits are traditionally used to enhance the flavor and nutritional value of various foods. They contain essential and glyceride oils, proteins, dietary fiber, carbohydrates, minerals, and other bioactive compounds. This study is aimed at determining the chemical composition of a commercial essential oil from caraway fruits, evaluating its antimicrobial activity against some of the most common foodborne test microorganisms, and assessing its antioxidant potential. The main components were identified in the oil, with the dominant compounds being the monoterpene ketone carvone (71.26%) and the monoterpene hydrocarbon limonene (27.71%). The antimicrobial effect of the essential oil was tested against Gram-positive (*Staphylococcus aureus)* and Gram-negative bacteria (*Escherichia coli, Salmonella enterica,* and *Listeria monocytogenes*). The results showed that only E. coli was sensitive to the tested concentrations, while no inhibitory effect was observed against the other three microorganisms at any level. The antioxidant activity was evaluated using two methods: DPPH (1443 μM TE/mL) and FRAP (1282.36 μM TE/mL). The high content of oxygenated compounds, particularly aldehydes, suggests notable biological activity of the essential oil, indicating its potential for inclusion in the formulation of various functional food products.

## 1 Introduction

Caraway (*Carum carvi* L.), Apiaceae family, is a biennial plant, native to Southeastern Europe. It has been cultivated in Egypt since as early as 1500 BCE. Caraway is an herbaceous plant that grows up to 1 meter tall. In the wild, it can be found across Europe, Asia, and North Africa. In Bulgaria, it grows naturally in meadows in the Central and Western Balkan Mountains, Rila, the Rhodope Mountains, and other regions.

All parts of the plant contain essential oil, but it is most concentrated in the mature fruits, ranging from 3% to 7%. The oil is an easily mobile, transparent, colorless to amber-yellow liquid with a typical spicy aroma and pungent, flavorful taste typical of caraway [1-4].

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The main constituents of caraway essential oil, accounting for more than 87% and up to 97% of the total composition, are carvone (over 50%) and limonene (up to approximately 45%). Their ratio changes with fruit maturity: as the fruit ripens, carvone content increases while limonene decreases. In commercial essential oils, which are often derived from batches with fruits at different stages of maturity, carvone typically ranges from 50–65%, and limonene up to 40%. Other minor components include dihydrocarvone and dihydrocarveol (together around 2%), carveol (about 0.3%), perillaldehyde (up to 1%), $\alpha$- and $\beta$-pinene, myrcene, $\beta$-caryophyllene, among others [5-9].

The high content of oxygenated monoterpenes, particularly aldehydes, contributes to the oil's antimicrobial [10-13] and antioxidant properties [10, 11], making it valuable in cosmetics, food production, and medicine [14].

Aromatic products derived from caraway, such as essential oil and resinoid, are used in the food industry, particularly in meat food, sausages, sauces, and alcoholic beverages like brandy, liqueurs, the German spirit "Kümmel," and the Scandinavian "Enips" [15].

In aromatherapy, caraway oil is used in baths, gargles, compresses, massages, and occasionally for inhalation. It is applied in cases of nervous tension, depression, general fatigue, headaches, colds, muscle pain, gastrointestinal discomfort and bloating, digestive atony, upper respiratory tract infections, sore throat and cough, urological conditions, and to repel skin parasites (e.g., ticks, lice, fleas). Due to its pronounced antimicrobial activity, it is increasingly applied in the food industry as a natural preservative [11-14].

In Bulgaria, caraway fruits are primarily used as a spice, while their industrial processing for essential oil production remains limited [1].

Therefore, the aim of this study is to determine the chemical composition of a commercial essential oil from caraway fruits, as well as to evaluate its antimicrobial activity against common foodborne test microorganisms and assess its antioxidant potential.

## 2 Material and methods

### 2.1 Essential oil

The commercial essential oil from caraway fruits (Fig. 1) was purchased from a supplier, harvested in 2024.

**Fig. 1.** Image of caraway (*Carum carvi* L.) fruits

### 2.2 Chemicals and reagents

High-purity solvents and analytical reagents needed for the HPLC and antioxidant assays were sourced from commercial suppliers, including Sigma-Aldrich.

### 2.3 Chemical composition of essential oils

Before GC-MS analysis, the essential oil was dried, derivatized, and injected into the instrument. The chromatographic separation and mass detection followed a standard temperature-programmed method, and compounds were identified by retention indices and spectral matching.

### 2.4 Antimicrobial activity of essential oils

Antimicrobial activity was assessed on reference strains of both Gram-positive and Gram-negative bacteria sourced from the national culture bank, using the method of Iacobellis and colleagues [12].

### 2.5 Antioxidant activity of essential oils

Antioxidant activity was assessed by DPPH and FRAP assays.

### 2.6 Statistical Analysis

All measurements were performed in triplicate and reported as mean ± SD. Differences between groups were assessed using one-way ANOVA with Tukey's test (SPSS 19.0), with significance set at $p < 0.05$.

## 3 Results and discussion

The commercial caraway essential oil is a mobile liquid with a characteristic aroma and light yellow color, whose chemical composition is presented in Table 1 and Fig. 2.

**Table 1.** Aromatic compounds in commercial essential oil from caraway fruits (TIC$^{a}$, %)

| Peak | RT$^{b}$, min | RI$^{c}$ | Compounds | Content |
|---|---|---|---|---|
| 1. | 12.51 | 1025 | Limonene | 27.71 ± 0.25 |
| 2. | 17.67 | 1188 | ciss-Dihydrocarvone | 0.34 ± 0.0 |
| 3. | 17.84 | 1192 | Neodihydrocarveol | 0.12 ± 0.0 |
| 4. | 18.82 | 1200 | trans-Dihydrocarvone | 0.18 ± 0.0 |
| 5. | 19.20 | 1246 | Carvone | 71.26 ± 0.70 |
| 6. | 19.93 | 1274 | Perillaldehyde | 0.13 ± 0.0 |
| 7. | 24.53 | 1458 | β-trans-Farnesene | 0.22 ± 0.0 |

$^{a}$ – Total Ion Current; $^{b}$ – RetentionTtime, min; $^{c}$ – Retention (Kovat's) Index.

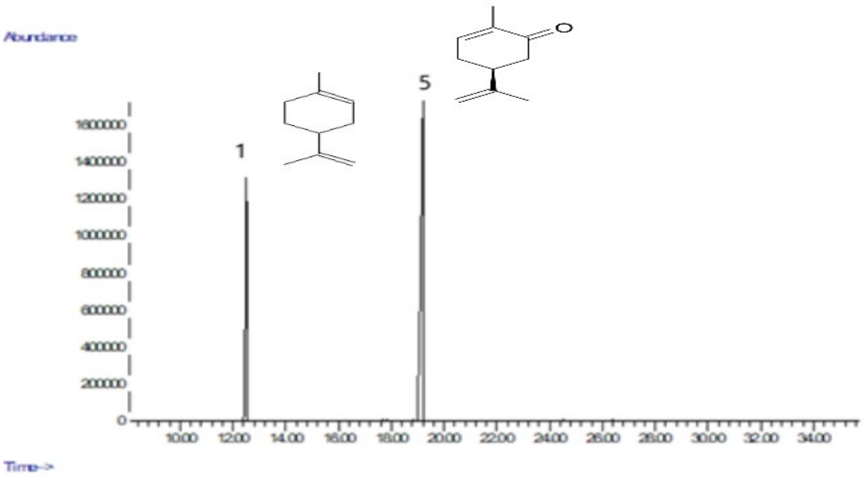



**Fig. 2.** Chromatogram of the saraway essential oil (The numbering is the same as in Table 1)

The analysis revealed a total of seven identified compounds, representing 100% of the total oil content. Among them, only two components were present in significant amounts, while the remaining five appeared in trace concentrations below 1%. The dominant constituents were carvone (71.26%) and limonene (27.71%)**,** which together accounted for nearly the entire composition of the essential oil.

This composition profile highlights carvone as the major bioactive component, followed by limonene, both of which contribute to the characteristic aroma and potential functional properties of caraway oil. The minor compounds, including cis-dihydrocarvone (0.34%), trans-dihydrocarvone (0.18%), neodihydrocarveol (0.12%), perillaldehyde (0.13%), and β-trans-farnesene (0.22%), were found in negligible amounts and are likely to play a limited role in the oil's overall activity and flavor profile.

The chemical composition observed is consistent with typical profiles reported for caraway essential oil, with minor variations in the relative proportions of components. For example, the study by Gajić et al. [4] identified twenty-six compounds extracted via headspace-solid phase microextraction (HS-SPME) and analyzed by GC-FID. In their volatile profile, the monoterpene hydrocarbons have the highest percentage (73.6%), followed by oxygen-containing monoterpenes (25.4%). This represents a reversed group distribution compared to our results, where oxygenated compounds were more prevalent [4]. Such differences can be attributed to various factors, including geographical origin, environmental conditions, harvesting time, extraction method, and instrumental sensitivity, all of which are known to influence the volatile composition of essential oils in aromatic plant species.

The ratio of the aromatic compounds in commercial essential oil from caraway fruits by chemical group is presented in Fig. 3. The results indicate a clear predominance of oxygenated monoterpenes**,** which comprise 72.06% of the total oil content. These are followed by monoterpene hydrocarbons at 22.27%**,** while sesquiterpene hydrocarbons were present in much smaller amounts, accounting for only 0.22% of the composition.

The main contributors to the aroma and biological properties of essential oils are typically the oxygenated compounds. Their distribution by functional group, shown in Fig. 4, revealed that ketones were the most abundant, with carvone as the principal representative. They were followed by smaller amounts of aldehydes and alcohols, which also contributed to the oil's overall functionality and scent profile.

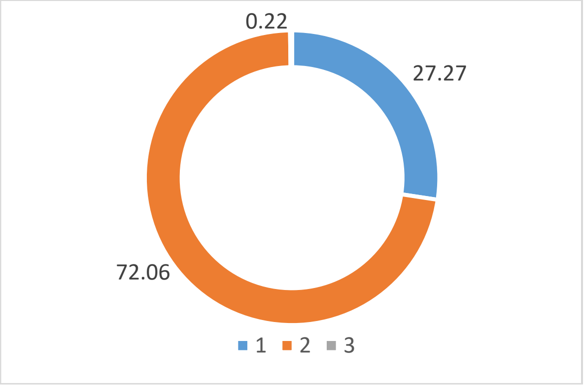



**Fig. 3.** Distribution of the components by group, %: 1 – monoterpene hydrocarbons; 2 – oxygenated monoterpenes; 3 – sesquiterpene hydrocarbons.

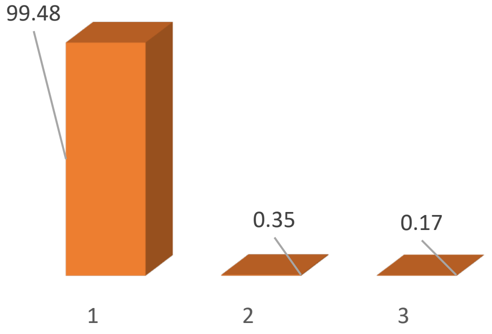



**Fig. 4.** Distribution of oxygenated compounds, %: 1 – ketones; 2 – aldehydes; 3 – alcohols.

The size of the zones of inhibition against the researched test-microorganisms can be seen in Tables 2 and 3.

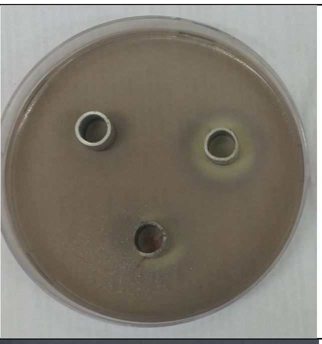
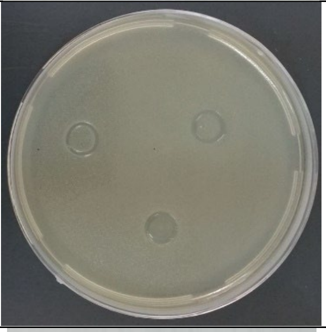
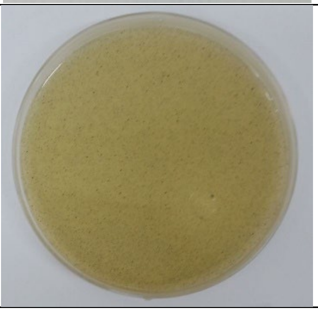
**Table 2**. Inhibition zones of caraway essential oil, mm.

| **Concentration of essential oil, mL** | | ***Escherichia coli*** | ***Salmonella enterica*** | ***Listeria mono cytogenes*** | ***Staphylococcus aureus*** |
|---|---|---|---|---|---|
| Caraway essential oil | 0.10 | 20 | - | - | - |
| | 0.07 | 17 | - | - | - |
| | 0.05 | -* | - | - | - |

* no effect.

The antimicrobial activity of commercial essential oil from caraway fruits was evaluated against four common foodborne pathogens: *Escherichia coli, Salmonella enterica, Listeria monocytogenes*, and *Staphylococcus aureus*, using three concentrations (0.10, 0.07, and 0.05 mL). The results showed that only *E. coli* was susceptible to the tested concentrations, while no inhibitory effect was observed against the other three microorganisms at any level tested.

**Table 3**. Inhibition zones of caraway essential oil.

| Test microorganism | *Inhibition zones* |
|---|---|
| *Escherichia coli* |  |
| *Salmonella enterica* |  |
| *Listeria monocytogenes* |  |
| *Staphylococcus aureus* |  |

At the highest concentration (0.10 mL), the inhibition zone against *E. coli* measured 20 mm, indicating moderate antibacterial activity. A decrease to 17 mm was observed at 0.07 mL, demonstrating a concentration-dependent effect. No inhibition was detected at 0.05 mL. The absence of activity against *S. enterica, L. monocytogenes*, and *S. aureus* may be related to structural differences in their cell envelopes and resistance mechanisms, particularly in

Gram-positive bacteria, which typically possess a thicker peptidoglycan layer. In comparison, Hajlaoui et al. [10] reported broader antimicrobial potential for caraway essential oil, with inhibition zones ranging from 11.00 mm to 25.00 mm against a panel of eighteen pathogenic strains. This suggests that caraway essential oil can be effective against a wider range of microorganisms under certain conditions. The differences may be attributed to variations in oil composition, concentration, and the types of test strains used in each study. Overall, both studies confirm the antibacterial potential of caraway essential oil, though the spectrum and strength of activity may vary.

On the other hand, our findings align with previous reports describing the selective antimicrobial activity of caraway oil, primarily attributed to its major constituents carvone and limonene, which exhibit higher efficacy against Gram-negative bacteria [12].

The antioxidant effect of commercial essential oil from caraway fruits was evaluated using the DPPH and FRAP assays, with results summarized in Table IV. The oil exhibited values of 1443 ± 0.01 µM TE/mL in the DPPH assay and 1282.36 ± 0.02 µM TE/mL in the FRAP assay, indicating moderate antioxidant potential.

The results can be seen in Table 4.

**Table 4**. Antioxidant activity of caraway essential oil.

| | **DPPH, µM TE/mL** | **FRAP, µM TE/mL** |
|---|---|---|
| **Caraway essential oil** | 1443 ± 0.01 [a] | 1282,360 ± 0.02 [a] |

* Values marked with different letters in the same row are statistically different at $p < 0.05$.

The higher value in the DPPH assay suggests that the oil is somewhat more effective at neutralizing free radicals than at reducing ferric ions. However, the close range of the two results reflects a balanced antioxidant profile. The activity is likely associated with the oil's major constituents, particularly carvone and limonene, which are known for their free radical scavenging and electron-donating properties.

In comparison, the study by Gajić et al. [4] reported antioxidant activity based on DPPH inhibition percentage, where caraway volatiles exhibited approximately 37% radical scavenging activity. Although the measurement units differ (µM TE/mL vs. % inhibition), the overall antioxidant capacity observed in their study was relatively lower. In another study, Hajlaoui et al. [10] reported an $IC_{50}$ value of 19.00 ± 1.00 mg/mL for DPPH and 11.33 ± 1.53 mg/mL for FRAP for caeaway essential oil, indicating antioxidant potential, though not as high as the combined oil blend with coriandrum (*Coriandrum sativum* L.). Their caraway oil had significantly lower carvone content (12.20%), and higher concentrations of γ-terpinene (31.03%), β-pinene (18.77%), and p-cymene (17.16%), compounds with weaker antioxidant effects compared to carvone. This kind of variation could be mainly due to differences in extraction methods and compound composition. The commercially distilled oil used in our study contained a higher proportion of carvone, a compound with strong antioxidant properties.

## 4 Conclusion

The chemical analysis of caraway essential oil revealed a simple composition dominated by carvone (71.26%) and limonene (27.71%), with a high proportion of oxygenated monoterpenes, mainly ketones. These aromatic coponents are largely responsible for the oil's typical aroma and bioactivity. The oil showed moderate antioxidant activity, as demonstrated by both DPPH and FRAP assays. Antimicrobial testing indicated selective efficacy against *Escherichia coli*, while no inhibitory effect was observed against *Salmonella enterica,* *Listeria monocytogenes,* or *Staphylococcus aureus*. In summary, caraway essential oil exhibits potential as a natural antioxidant and selective antimicrobial agent, supporting its application in food preservation and related industries. Further research is needed to expand its functional applications and evaluate its broader antimicrobial spectrum.

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