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Time-Dependent Effects of Caraway Essential Oil on the Total Antioxidant Capacity of Rapeseed, Olive, and Grapeseed Oils

Maryna Opryshko[1], Halina Tkaczenko*[2], Oleksandr Gyrenko[1], Myroslava Maryniuk[1], Lyudmyla Buyun[1], Natalia Kurhaluk[2]

[1]M.M. Gryshko National Botanic Gardenof the National Academy of Science of Ukraine, Kyiv, Ukraine
[2]Institute of Biology, Pomeranian University in Słupsk, Słupsk, Poland

Maryna Opryshko: https://orcid.org/0000-0001-5048-4961
Halina Tkaczenko: https://orcid.org/0000-0003-3951-9005
Oleksandr Gyrenko: https://orcid.org/0000-0003-3296-3787
Myroslava Maryniuk: https://orcid.org/0000-0003-2590-448X
Lyudmyla Buyun: https://orcid.org/0000-0002-9158-6451
Natalia Kurhaluk: https://orcid.org/0000-0002-4669-1092

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The use of essential oils in food preservation supports innovation in food technology and the development of healthier and more sustainable foods for consumers. The incorporation of essential oils into edible oil formulations or food products can help to extend shelf life, improve sensory attributes, and maintain nutritional quality, thus contributing to the development of healthier and more sustainable food products. This study aimed to investigate the effects of commercial caraway essential oil (CEO) as an antioxidant on the total antioxidant capacity (TAC) of rapeseed, olive, and grapeseed oils during 120 days of storage. Commercial CEO was provided by the Polish essential oil producer (Etja, Elbląg, Poland). The rapeseed, olive, and grapeseed oil samples (5 mL) were incubated with 0.1 mL CEO (final concentration 20 μg·mL^{-1}) at 25 °C for 240 days. This reaction mixture was gently shaken at fixed intervals during incubation at 25 °C. Samples were collected for analysis after 0, 8, 15, 30, 60, and 120 days of storage. The rapeseed, olive, and grapeseed oil samples without additives were used as control samples. These oils showed different responses to the addition of CEO at different time intervals, highlighting the importance of considering temporal dynamics when assessing antioxidant effects. The addition of CEO to rapeseed oil increased the TAC in rapeseed oil at 30 and 120 days of storage, while the addition of CEO to olive oil increased the TAC at 30 and 60 days of storage. The addition of the CEO increased the TAC in grapeseed oil at 7, 30, and 120 days of storage. Our results suggest that the addition of CEO did not increase the antioxidant capacity of rapeseed and olive oils, especially during the early stages of storage. However, this effect changed over time, indicating a time-dependent increase in antioxidant potency. Interestingly, grapeseed oil showed a sustained increase in TAC after the incorporation of CEO after 30 days of storage, suggesting a potential synergistic relationship between the two components that warrants further investigation. Further research is warranted to optimise antioxidant formulations, elucidate underlying mechanisms, and assess safety considerations for wider use in food preservation and other food industry applications.

Keywords: caraway essential oil, *Carum carvi*, antioxidant, edible oils, storageKeywords: *Actinidia arguta*, *Schisandra chinensis*, *Malus domestica*, *Cornus mas*, *Chaenomeles japonica*, mixed plantings, photosynthetic pigments, nitrate nitrogen

***Corresponding Author:** Halina Tkaczenko, Institute of Biology, Pomeranian University in Słupsk, Arciszewski 22b, 76-200 Słupsk, Poland
halina.tkaczenko@upsl.edu.pl

Introduction

Edible oils are susceptible to oxidative degradation, resulting in the formation of harmful compounds such as free radicals, peroxides, and aldehydes, which can adversely affect flavour, aroma, nutritional value, and overall product quality (Flores et al., 2021; Chemat et al., 2023). When oils encounter air and moisture, they undergo a process known as auto-oxidation, which results in the appearance of odours, flavours, and abnormal colours, the formation of potentially toxic compounds, and a reduction in the usefulness of the product. To prolong the useful life of oils and to obtain good quality products when heated, antioxidants are added, ideally a mixture of antioxidants, as they have a synergistic effect and provide greater protection (Flores et al., 2021).

Antioxidants play a crucial role in inhibiting or retarding oxidative processes by scavenging free radicals and stabilising lipid molecules, thereby extending the shelf life and preserving the sensory properties of edible oils (Serafini and Peluso, 2016; Petcu et al., 2023). In recent years, there has been growing interest in the use of essential oils as natural antioxidants to extend the shelf life and improve the stability of edible oils (Stevanović et al., 2018; Sharma et al., 2021; Ojeda-Piedra et al., 2022; Matera et al., 2023). Among these essential oils, caraway essential oil (CEO) has attracted attention due to its potent antioxidant properties and potential applications in food preservation (Mohsenzadeh, 2007).

Carum carvi L. (Apiaceae Lindl.), or caraway, is a common household plant cultivated throughout the world (Keshavarz et al., 2013; Rasooli and Allameh, 2016). Dried fruits of annual caraway contain between 2.8 and 3.3% oil, while those of biennial caraway contain between 3.9 and 5.0% oil. The CEO is a transparent, colourless, or slightly yellowish liquid, characterised by a pleasantly spicy aroma and a slightly pungent taste (Gniewosz et al., 2013). The essential oil contains about 30 chemical compounds, the main ones being carvone and limonene, the total content of which is about 95%, regardless of the plant's origin (Sedláková et al., 2003; Labiri et al., 2010).

Caraway is used to flavour foods and beverages and has several traditional uses in ethnomedicine. In traditional medicine, the galactagogic and carminative effects of caraway are superior to other biological effects. The anti-inflammatory, antispasmodic, antimicrobial, antioxidant, carminative, and immunomodulatory properties of caraway suggest that it has been traditionally used for a long time for various medical prescriptions such as digestive disorders, including gas, loss of appetite, flatulence, heartburn, and mild spasms of the stomach and intestines (Keshavarz et al., 2013; Hajlaoui et al., 2021). Caraway has been used to treat many human ailments and the antiepileptic, anti-inflammatory, and galactagogic effects of CEO have been confirmed in preclinical studies (Mahboubi, 2019). Traditionally, CEO has been used to help people avoid phlegm, relieve constipation, and control urination. Nursing mothers use caraway to increase breast milk flow (Kabiri et al., 2017). Caraway reduces plasma triglyceride and cholesterol levels in normal and streptozotocin rats (Lemhadri et al., 2006). Many pharmacological properties of caraway have been demonstrated, such as anticonvulsant, antimicrobial, analgesic, anti-inflammatory, anti-anxiety, anti-hyperglycaemic and antispasmodic properties, and it has been used as a remedy for digestive disorders, functional dyspepsia, thyroid hormone imbalance, flatulence and hysteria (Hajlaoui et al., 2021), as well as a remedy for indigestion, pneumonia, carminative, appetizer and galactagogue (Mahboubi, 2019).

However, the efficacy of CEO as an antioxidant can vary depending on factors such as concentration, exposure time and composition of the oil matrix (Strasakova et al., 2021). Understanding the time-dependent effects of CEO on the total antioxidant capacity of commonly used edible oils such as rapeseed, olive and grapeseed oils is essential to optimise their antioxidant efficacy and ensure product quality and safety. Time-dependent studies are essential to assess the stability and longevity of antioxidant activity over long storage periods and to elucidate the kinetics of antioxidant-oil interactions (Datsenka et al., 2019; Opryshko et al., 2021).

This study aimed to investigate the time-dependent effects of commercial CEO (Etja, Elblag, Poland) as an antioxidant substance on the total antioxidant capacity (TAC) of rapeseed, olive and grapeseed oils during 120 days of storage to evaluate the antioxidant capacity of CEO for the storage of edible oils.

Material and methodology

Caraway essential oil

The commercial CEO was provided by the Polish essential oil manufacturers (Etja, Elbląg, Poland). The composition of CEO: (INCI: Carum Carvi Oil), limonene, linalool. Samples were stored in reclosable vials at 5 °C in the dark and allowed to equilibrate to room temperature before testing. Geographical origin was excluded as this information was mostly not available.

The rapeseed, olive, and grapeseed oil samples (5 ml) were incubated with 0.1 ml CEO (final concentration 20 μg·mL^{-1}) at 25 °C for 240 days. This reaction mixture was gently shaken at fixed intervals during incubation at 25 °C. Samples were collected for analysis after 0, 8, 15, 30, 60, and 120 days of storage. The rapeseed, olive, and grape seed oil samples without additives were used as control samples.

Rapeseed, olive, and grapeseed oils

The rapeseed, olive, and grapeseed oils were purchased from a local shop. Rapeseed oil (Wyborny, Poland) is refined rapeseed oil. The energy value of 100 ml is 3,464 kJ (828 kcal), fat 92 g, including 6.4 g saturated fatty acids, 58 g monounsaturated fatty acids, and 28 g polyunsaturated fatty acids.

Olive oil (Casa de Azeite, Italy) is a high-quality extra virgin olive oil. The energy value of 100 ml is 3,374 kJ (821 kcal), fat 91 g, including 13 g of saturated fatty acids, 72 g of monounsaturated fatty acids, and 6.3 g of polyunsaturated fatty acids.

Grapeseed oil (Monini, Italy) is a product containing polyunsaturated fatty acids. The energy value of 100 ml is 3,404 kJ (828 kcal), fat is 92 g, including 11 g of saturated fatty acids, 24 g of monounsaturated fatty acids, and 57 g of polyunsaturated fatty acids.

Measurement of total antioxidant capacity (TAC)

The level of TAC in the samples was estimated by measuring the level of 2-thiobarbituric acid reactive substances (TBARS) after oxidation of Tween-80. This level was determined spectrophotometrically at 532 nm (Galaktionova et al., 1998). The sample inhibits the Fe^{2+}/ascorbate-induced oxidation of Tween 80, resulting in a decrease in the 2-thiobarbituric acid reactive substances (TBARS) levels. Briefly, 0.1 mL of oil sample was added to 2 mL of 1% Tween-80 reagent, 0.2 mL of 1 mM $FeSO_4$ and 0.2 mM of 10 mM ascorbic acid. In the blank assay, 0.1 mL of distilled water was used in place of the sample. The mixture was incubated for 48 hours at 25 °C. After cooling, 1 mL of 20% trichloroacetic acid was added. The mixture was centrifuged at 3,000 rpm for 10 minutes. After centrifugation, 2 mL of the supernatant was mixed with 2 mL of 0.25% 2-thiobarbituric acid reagent. The mixture was heated in a boiling water bath at 95 °C for 15 min. The mixture was cooled and the absorbance of the resulting solution was measured at 532 nm. The absorbance of the blank was defined as 100%.

Statistical analysis

Results are expressed as mean values. All variables were tested for normal distribution using the Kolmogorov-Smirnov test ($p > 0.05$). The significance of differences in TAC levels between samples (significance level $p < 0.05$) was tested using the Mann-Whitney test according to Zar (1999). All statistical calculations were performed on separate data from each sample using STATISTICA software v. 13.3 (TIBCO Inc., USA).

Results and discussion

Total antioxidant capacity (TAC) is an analyte often used to evaluate the antioxidant status of biological samples and can assess the antioxidant response to free radicals produced in a given condition (Rubio et al., 2016). The effect of CEO addition and storage time on the TAC of rapeseed, olive, and grapeseed oils at 7, 15, 30, 60, and 120 days of storage is shown in Figures 1–3.

The total antioxidant capacity of rapeseed oil after 7, 15, 30, 60, and 120 days of storage was decreased by 13.4%, 15.8%, 51.2%, 45.9%, and 19.4% respectively compared to the beginning of the study (0 days). The total antioxidant capacity in rapeseed oil with added CEO after 7, 15, 30, 60, and 120 days of storage was also reduced by 16.5%, 15.1%, 26.7%, 47.5%, and 13.5% respectively compared to the beginning of the study (0 days). The addition of CEO to rapeseed oil increased the TAC in rapeseed oil at 30 and 120 days of storage by 44.48% ($p < 0.05$) and 3.25% ($p > 0.05$), respectively, compared to the control samples (rapeseed oil). At 7, 15, and 60 days, a non-significant decrease in TAC levels was observed compared to the control samples (by 7.26%, 2.95%, and 6.40%, $p > 0.05$) (Figure 1).

The total antioxidant capacity of olive oil after the addition of CEO at 7, 15, 30, 60, and 120 days of storage is shown in Figure 2.

The total antioxidant capacity of the olive oil after 7, 15, 30, 60, and 120 days of storage was reduced by 14.4%, 25.2%, 32.9%, 32.5%, and 19.9% respectively compared to the beginning of the study (0 days). The total antioxidant capacity in the olive oil with added CEO after 7, 15, 30, 60, and 120 days of storage was also decreased by 13.7%, 21.4%, 17.2%, 17.8%, and 8.7% respectively compared to the beginning of the study (0 days). The addition of CEO increased the TAC level in olive oil at 30 and 60 days of storage by 8% ($p > 0.05$) and 6.57% ($p > 0.05$), respectively, compared to the control samples (olive oil). At 7, 15, and 120 days, a non-significant decrease in TAC levels was observed

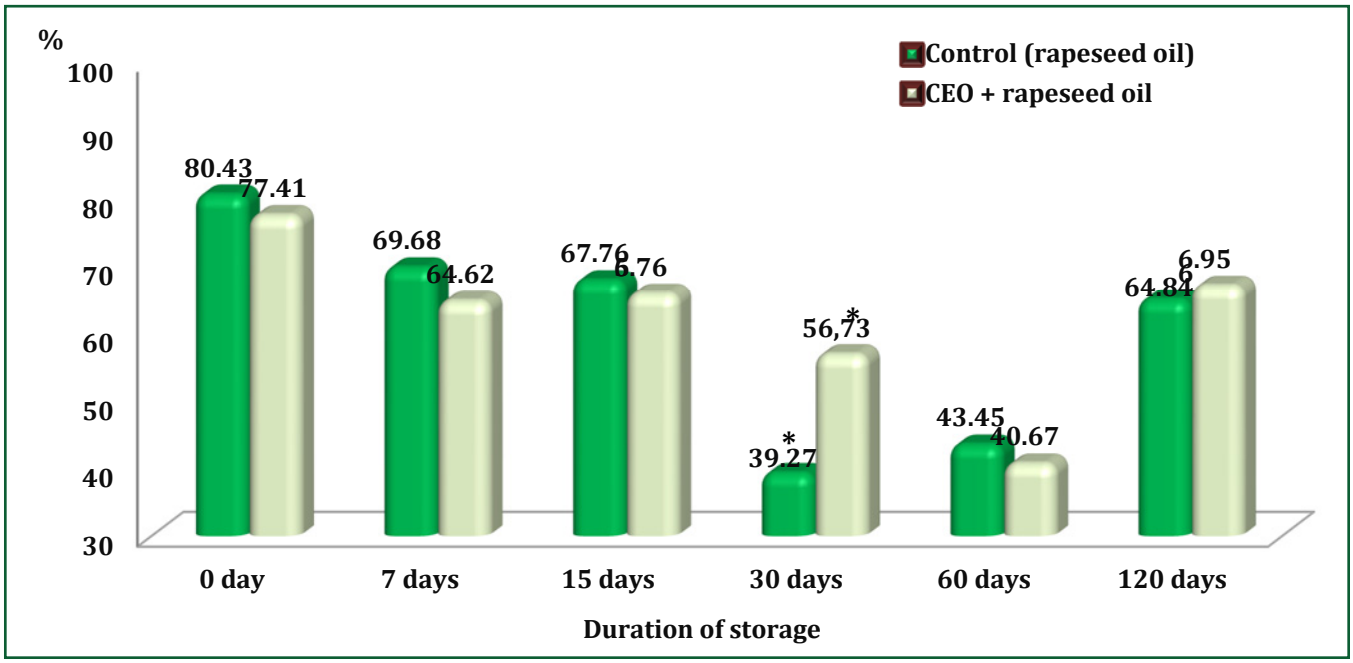

Figure 1 Effect of CEO addition and storage time on the total antioxidant capacity (TAC, %) of rapeseed oil after 7, 15, 30, 60, and 120 days of storage
* Changes are significantly different between control and CEO addition ($p < 0.05$, $n = 6$)

compared to the control samples (by 11.81%, 8.04%, and 0.25%, $p > 0.05$) (Figure 2).

The total antioxidant capacity of grapeseed oil after the addition of CEO at 7, 15, 30, 60, and 120 days of storage is shown in Figure 3.

The total antioxidant capacity of grapeseed oil after 7, 15, 30, 60, and 120 days of storage was decreased by 6.21%, 12.9%, 19.41%, 22.4%, and 14.27% respectively compared to the beginning of the study (0 days). The total antioxidant capacity in grapeseed oil with added CEO after 7, 15, 30, 60, and 120 days

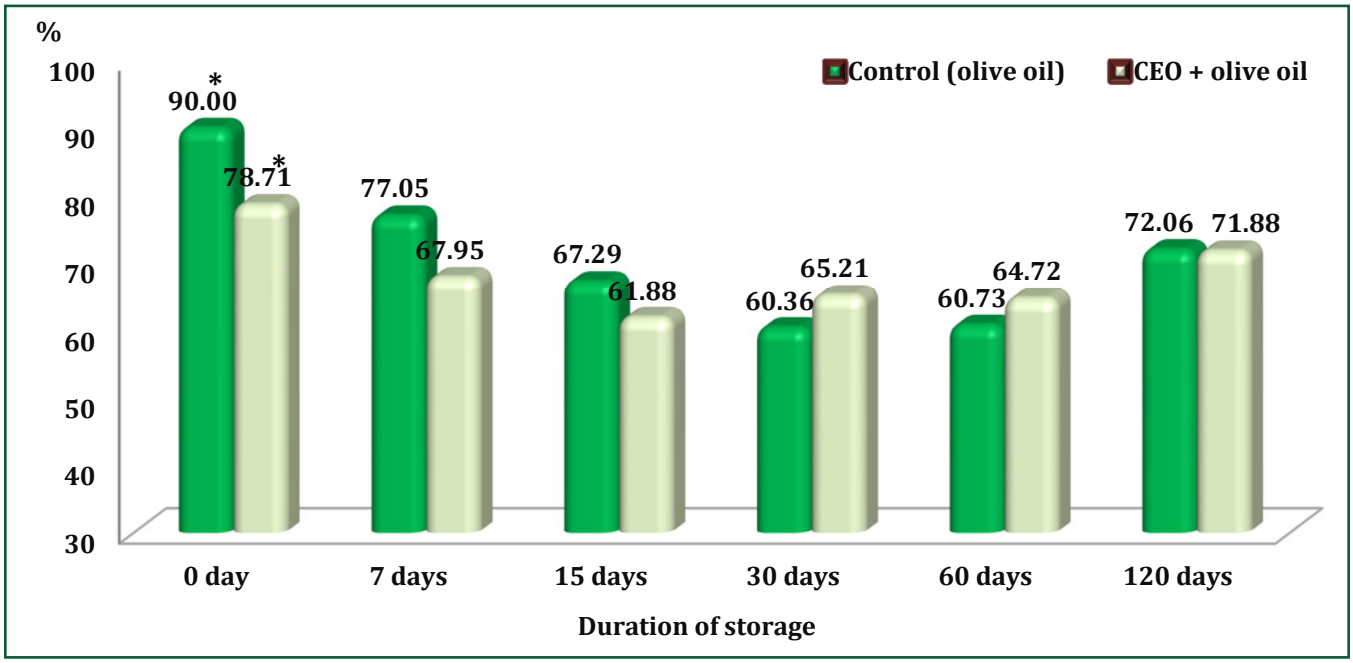

Figure 2 Effect of CEO addition and storage time on the total antioxidant capacity (TAC, %) of olive oil after 7, 15, 30, 60, and 120 days of storage
* Changes are significantly different between control and CEO addition ($p < 0.05$, $n = 6$)

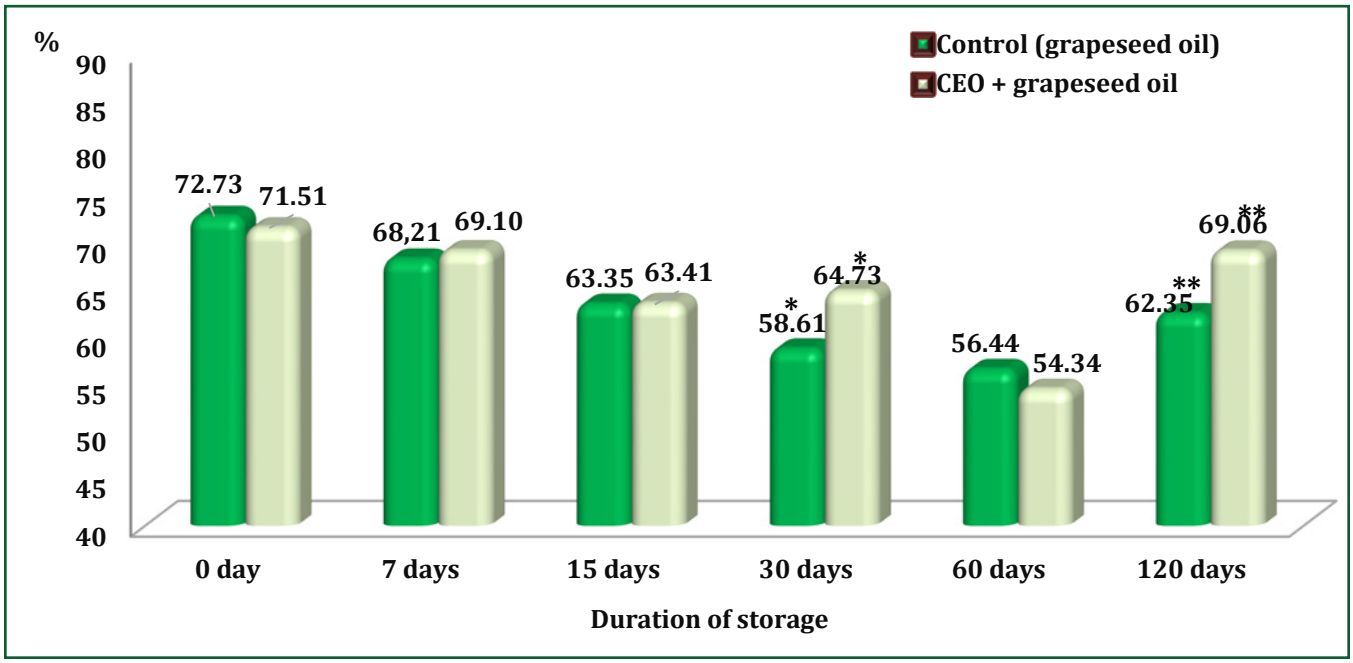

Figure 3 Effect of CEO addition and storage time on total antioxidant capacity (TAC, %) in grapeseed oil after 7, 15, 30, 60, and 120 days of storage
* and ** – changes are significantly different between control and CEO addition ($p < 0.05$, $n = 6$)

of storage was also decreased by 3.37%, 11.33%, 9.482%, 24%, and 3.43% respectively compared to the beginning of the study (0 days). The addition of CEO increased the TAC in grapeseed oil at 7, 30, and 120 days of storage by 1.3% ($p < 0.05$), 10.44% ($p < 0.05$), and 10.76% ($p > 0.05$) respectively compared to the control samples (grapeseed oil). At 0 and 60 days, a non-significant decrease in TAC levels was observed compared to the control samples (by 1.68% and 3.72%, $p > 0.05$) (Figure 3).

Our results show that the addition of CEO significantly increases the total antioxidant capacity of rapeseed, olive, and grapeseed oils after 30 days. This observation suggests that CEO has antioxidant properties capable of scavenging free radicals and stabilising lipid molecules, thereby delaying the onset of oxidative deterioration in edible oils. Time course analysis reveals dynamic changes in antioxidant activity, with different rates of change in TAC, observed for different oils and incubation times. For example, the addition of CEO to all oils tested for 30 days resulted in a non-significant decrease in TAC levels. After 31 days, an increase in TAC levels was observed for all oils tested, and for rapeseed and grapeseed oils these increases were statistically significant ($p < 0.05$) (Figure 1–3). After 120 days of incubation, TAC levels were statistically significantly increased in grapeseed oil. These time-dependent effects highlight the importance of considering the kinetics of antioxidant-oil interactions when evaluating the efficacy of natural antioxidants in food preservation applications. The composition of the oil matrix (rapeseed, olive, and grapeseed oils), including the fatty acid profile, lipid content, and presence of natural antioxidants, may also influence the efficacy of CEO as an antioxidant. Further research is needed to elucidate the underlying mechanisms governing the interactions between CEO and different oil matrices and to optimise antioxidant formulations for specific applications.

Caraway oil is found in all parts of the plant, but its concentration is highest in the fruits. It is extracted by hydro-distillation. Caraway seed oil is obtained by hydrodistillation of the husks and stems and contains less carvone and more terpenes. Caraway oleoresin is obtained from crushed dried caraway seeds using solvents (hexane-ethanol, ethyl acetate, ethylene dichloride) and has a greenish yellow colour, usually containing essential oil (20–25%) and fixed oil (60–75%). Environmental conditions have a significant effect on seed quality, in other words, hot and dry weather is associated with significantly lower quality fruit (Mahboubi, 2019). CEO was characterised in terms of the chemical profile of volatile terpenoid compounds prior to its addition to meat products (Tomović et al., 2022). Carvone (77.00%) was identified as the predominant compound in CEO, followed by d,l-limonene (18.05%). The content of two major terpenoids was followed by dihydrocarvone (1.05%),

while all other detected volatiles were observed in <1% relative percentage (Tomović et al., 2022).

Previous studies have suggested potential synergistic interactions between CEO and other natural antioxidants or food additives, further enhancing their combined antibacterial activity. The antibacterial activity of essential oils prepared from three Apiaceae species was evaluated against several food-borne pathogens, namely *Staphylococcus aureus*, *Bacillus cereus*, *E. coli* O157:H7, *Salmonella enteritidis*, and *Listeria monocytogenes*. According to this experiment, the minimum inhibitory concentration (MIC) ranges of the oils were 0.03–0.5, 0.18–3.0, and 0.37–3.0 mg·mL^{-1} for *Carum copticum*, *Bunium persicum*, and *C. cyminum*, respectively. It was also found that the combination of *B. persicum* and *C. cyminum* EOs confirmed synergistic and additive activities against the pathogens (Oroojalian et al., 2010).

Carvone is an important monoterpene ketone component (2-methyl-5-(1-methylethenyl)-2-cyclohexen-1-one) commonly isolated from *Carum carvi*, *Anethum graveolens* L. and *Mentha spicata* L. EOs. This component showed prominent antibacterial, antifungal, anticancer, anti-inflammatory and antioxidant activities, expanding its use in the pharmaceutical, food and packaging industries (Bouyahya et al., 2021). The antibacterial activity of carvone has been investigated by several authors against different strains such as *Escherichia coli*, *S. aureus*, *Streptococcus faecalis* and *Pseudomonas aeruginosa*. Different enantiomers have been used in comparative studies to evaluate the structure-function relationship (Demirci et al., 2004; Mun et al., 2014; Chan et al., 2016; Porfírio et al., 2017; Bouyahya et al., 2021).

Carvone has been investigated by various researchers for its antioxidant activity. One of the first investigations on the antioxidant properties of carvone isolated from *Mentha spicata* L. was carried out by Elmastaş et al. (2006). The results of the total antioxidant activity test indicated that S-carvone possessed high antioxidant activity compared to α-tocopherol, which was used as a reference antioxidant. Carvone has also been investigated for its antioxidant potential using different *in vitro* systems including lipid peroxidation, 2,2-dipenyl-1-picrylhydrazyl (DPPH) and phosphomolybdenum assay (Sabir et al., 2015). In this study, carvone isolated from *Zanthoxylum alatum* Wall. (syn. *Zanthoxylum armatum* DC.) showed inhibitory activity against 2-thiobarbituric acid reactive species (TBARS) induced by some pro-oxidants (10 μM $FeSO_4$ and 5 μM sodium nitroprusside) in rat liver and brain homogenates. Carvone also scavenged the DPPH radical and reduced molybdenum, Mo(VI) to Mo(V). Galstyan et al. (2018) documented the antioxidant property of a synthesis of carvone-derived 1,2,3-triazoles. The prepared conjugates showed high antioxidant activity.

The potent antioxidant activity of CEO is promising for its application in food preservation, particularly in the stabilisation of edible oils susceptible to oxidative degradation. The incorporation of CEO into edible oil formulations and food products may help to extend shelf life, improve sensory attributes, and maintain nutritional quality, thus contributing to the development of healthier and more sustainable food products (Gniewosz et al., 2013; Krkic et al., 2018; Tomović et al., 2022). The effect of caraway meal on fish growth and performance was evaluated by supplementing fish diets with different concentrations of caraway meal (5, 10, 15, and 20 g·kg^{-1}). The data obtained over a period of 12 weeks showed that fish weight gain and feed conversion ratio were significantly increased in fish-fed diets containing caraway seed meal at 10 g·kg^{-1} (Ahmad and Abdel-Tawwab, 2011). The use of caraway as a feed additive in fish diets affected the growth performance, feed utilisation, and total body composition of *Nile tilapia*, *Oreochromis niloticus* (L.) fingerlings.

Gniewosz et al. (2013) evaluated the antimicrobial efficacy of pullulan films containing CEO. The films were prepared from a 10% pullulan containing from 0.12% to 10.0% CEO. The antimicrobial activity of CEO was evaluated by the serial microdilution method and the films containing CEO were evaluated by the agar diffusion method against selected Gram-negative, Gram-positive bacteria and fungi. Analyses were also carried out to determine the efficacy of a pullulan coating with 10% CEO on baby carrots experimentally inoculated with *Salmonella enteritidis*, *Staphylococcus aureus*, *Saccharomyces cerevisiae* or *Aspergillus niger* and stored at room temperature for 7 d. At a concentration of 0.12%, CEO inhibited the growth of all microorganisms tested. Pullulan films containing 8–10% CEO were active against all microorganisms tested. *S. enteritidis* was the most resistant of the species tested, as it was not significantly reduced after 7 days of storage. At the end of storage, samples treated with the pullulan-caraway oil coating retained better visual acceptability than control samples. The results of this study suggest the feasibility of using a pullulan film with incorporated CEO to extend the microbiological stability of minimally processed foods (Gniewosz et al., 2013).

Krkic et al. (2013) reported that a chitosan-caraway coating, prepared with 0.20% CEO, was useful for the preservation of dry fermented sausages. This natural coating was able to protect the food from lipid oxidation, and maintained higher odour and taste scores after storage for five months. The results obtained by Tomović et al. (2022) suggested that CEO (0.01 $\mu l \cdot g^{-1}$) could be used as a safe antioxidant and an effective substitute for sodium nitrite in the processing of dry fermented sausages.

In the study by Das et al. (2024), carvone loaded chitosan nanoemulsion film (Carvone-Ne) was developed by ionic gelation and its functionality to prolong the shelf life of sliced bread was observed by inhibiting *Aspergillus flavus* contamination and aflatoxin B1 (AFB1) production. Carvone-Ne film showed better antifungal and AFB1 inhibitory activity than unencapsulated carvone. The antifungal and anti-AFB1 efficacy was attributed to disruption of ergosterol biosynthesis, release of ionic components and suppression of methylglyoxal production in *A. flavus* cells together with *in silico* interaction of carvone with Afl-R protein leading to impairment of AFB1 synthesis. The application of carvone-Ne nanoemulsion as an antifungal film on sliced bread showed a significant effect on quality attributes. During the *in situ* study, the carvone-Ne film effectively inhibited *A. flavus* proliferation and AFB1 production in sliced bread under storage conditions (25 ±2 °C and 75% RH) for 15 days. Furthermore, the carvone-Ne film coating maintained the CO_2 and O_2 composition of the sliced bread without altering the sensory properties. Thus, the novel carvone-Ne coating could be recommended as a promising smart and nano-based innovative packaging material to prolong the shelf life of slice breads along with a green insight to combat the health effects of petro-plastic coatings (Das et al., 2024).

The optical isomers of carvone can impart certain flavours to foods, and when creating functional fat-containing products, it is possible to use both optical forms of carvone, depending on the orientation of a new functional product. Research by Frolova et al. (2021) on the method of accelerated oxidation has shown that the introduction of carvone in the form of optical isomers into sunflower oil leads to an increase in the concentration of fatty products by 2.4–3.0 times in the values of the peroxide number and 1.5–1.7 times in the values of the acid number in comparison with the control. Comparing the effect of the optical isomers of carvone on the oxidation dynamics of fatty products, it was found that in general their protective effect is similar. However, the left carvone shows a greater effect on the resistance of sunflower oil compared to the right carvone. In addition to protection against oxidation, the optical isomers of carvone may have a physiological effect on the human body (Frolova et al., 2021).

Understanding how natural additives such as essential oils affect antioxidant capacity over time can inform strategies for preserving the quality and extending the shelf life of edible oils. This knowledge is essential for the food industry to maintain product integrity and safety (Ojeda-Piedra et al., 2022; Teshome et al., 2022). Research into their time-dependent antioxidant effects can contribute to the development of environmentally friendly solutions for food preservation in line with the sustainability goals of the food industry. With increasing consumer demand for natural and clean-label products, there is growing interest in replacing synthetic antioxidants with natural alternatives. Studies investigating the time-dependent effects of essential oils provide valuable insights into the efficacy of these natural additives and their potential application in food processing (Santiesteban-López et al., 2022).

By understanding the time-dependent effects of essential oils on antioxidant capacity, researchers can identify optimal formulations that maximise the health benefits of edible oils (Pezantes-Orellana et al., 2024). By studying how different oils interact with essential oils over time, researchers can optimise formulations to improve antioxidant stability and minimise undesirable effects such as flavour degradation or rancidity (Taghvaei and Jafari, 2015). This optimisation process is essential for the development of effective and commercially viable products. Understanding the effect of essential oils on the antioxidant capacity of edible oils may also have implications for culinary practices and may can guide the selection of edible oils and ingredients to maximise both flavour and nutritional value in food preparation.

Conclusions

In conclusion, our study demonstrates the time-dependent effect of CEO on the TAC of rapeseed, olive, and grapeseed oils. These oils showed different responses to the addition of CEO at different time intervals, highlighting the importance of considering temporal dynamics when assessing antioxidant effects. The addition of CEO to rapeseed oil increased the TAC in rapeseed oil at 30 and 120 days of storage, while the addition of CEO increased the TAC in olive oil at 30 and 60 days of storage. The addition of CEO increased the TAC in grapeseed oil at 7, 30, and 120 days of storage.

Our results suggest that the addition of CEO did not increase the antioxidant capacity of rapeseed and olive oils, especially during the early stages of storage. However, this effect changed over time, indicating a time-dependent increase in antioxidant potency. Interestingly, grapeseed oil showed a sustained increase in TAC after the incorporation of CEO after 30 days of storage, suggesting a potential synergistic relationship between the two components that warrant further investigation.

Overall, our study highlights the importance of considering the temporal dynamics of antioxidant effects when evaluating the efficacy of natural additives such as caraway essential oil in improving the oxidative stability of edible oils. Further research is needed to elucidate the underlying mechanisms driving these time-dependent effects and to optimise the use of such additives in food preservation applications. Future research could explore the synergistic effects of CEO in combination with other antioxidants or preservatives to develop synergistic antioxidant systems with improved efficacy and stability. Although CEO is generally recognised as safe for use in foods, it is important to consider potential safety concerns associated with its concentration and consumption. Future studies should address safety considerations, including maximum acceptable levels of CEO in foods and potential allergenic or adverse effects in susceptible individuals.

Conflicts of interest

The authors have no competing interests to declare.

Ethical statement

This article does not include any studies that would require an ethical statement.

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