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Effect of Cinnamon Essential Oil on the Oxidative Stability of Rapeseed, Olive, and Grapeseed Oils During Long-Term Storage

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The oxidative stability of edible oils affects their nutritional quality and shelf life. This study examined the impact of cinnamon essential oil (CEO) on the antioxidant capacity and lipid oxidation of rapeseed, olive, and grapeseed oils during extended storage periods (7–120 days). Total antioxidant capacity (TAC) and 2-thiobarbituric acid reactive substances (TBARS) were used as indicators of antioxidant status and lipid peroxidation, respectively. Throughout storage, TAC decreased and TBARS levels increased progressively in all control samples, confirming time-dependent oxidative deterioration. Adding CEO significantly increased TAC values in rapeseed and olive oils, especially after 30 and 120 days, with increases of up to 45.7 and 19.2%, respectively, compared to the control group ($p < 0.05$). In grapeseed oil, however, the CEO-induced enhancement of antioxidant capacity was transient, with significant increases at 7, 15, and 120 days, but inconsistent effects during mid-storage. Lipid peroxidation, as assessed by TBARS, was strongly influenced by both oil type and storage duration. CEO supplementation reduced TBARS accumulation in rapeseed and grapeseed oils after 60 days (by 18.3 and 36.6%, respectively), indicating a temporary protective effect. However, it occasionally exhibited pro-oxidant behaviour during the initial or final stages of storage. Among the oils tested, olive oil exhibited the highest oxidative stability and the most consistent antioxidant response to the addition of CEO. Thus, cinnamon essential oil demonstrated matrix-dependent and time-specific antioxidant and prooxidant properties. It effectively enhanced the oxidative stability of monounsaturated oils, but its performance was inconsistent in polyunsaturated systems. These findings highlight the potential of cinnamon essential oil as a natural, clean-label antioxidant additive for extending the shelf life of edible oils, provided its concentration and formulation are optimised for the oil matrix.

Keywords: Cinnamon essential oil, edible oils, antioxidant capacity, lipid peroxidation, storage stability, natural preservatives

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Introduction

Vegetable oils are an essential component of the human diet, providing energy and bioactive compounds such as unsaturated fatty acids, tocopherols, and phytosterols (Ma et al., 2023). However, their nutritional and sensory quality deteriorates over time due to oxidation processes that occur during storage, processing, and cooking. These processes lead to the formation of peroxides, aldehydes, and other secondary products that are responsible for rancidity and off-flavours, as well as reducing the shelf life of oils (Choe and Min, 2006; Gharby et al., 2025). Oils' susceptibility to oxidative degradation largely depends on their fatty acid composition: polyunsaturated oils, such as grapeseed and rapeseed oils, are considerably more prone to oxidation than olive oil, which is rich in monounsaturated fatty acids (Maszewska et al., 2018). Therefore, the search for natural antioxidants that can prevent or slow lipid peroxidation has become a key area of focus in food technology and nutrition research. This is particularly critical given the growing demand for food products with a prolonged shelf life and minimal synthetic additives (Rabiej-Kozioł et al., 2022; Yurchenko and Saealle, 2025).

Synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tert-butylhydroquinone (TBHQ) have long been used to stabilise edible oils. However, growing consumer concern about their potential health risks, coupled with regulatory restrictions on their use, has intensified interest in natural alternatives (Frankel et al., 1994; Pokorný, 2007). Among plant-derived antioxidants, essential oils (EOs) have attracted particular attention due to their multifunctional properties, including antimicrobial, antioxidant, and anti-inflammatory activities (Burt, 2004; Dhifi et al., 2016). These oils are complex mixtures of terpenoids, phenylpropanoids and other volatile compounds that can scavenge free radicals and chelate pro-oxidant metals. Using them as natural stabilisers in food systems is a sustainable and consumer-friendly way of extending product shelf life (Redondo-Cuevas et al., 2017). Moreover, the incorporation of essential oils aligns with current trends favouring clean-label ingredients (Bibow and Oleszek, 2024).

Cinnamon essential oil (CEO), obtained mainly from *Cinnamomum zeylanicum* or *Cinnamomum cassia*, contains cinnamaldehyde, eugenol, and coumarin as its main bioactive constituents (Guo et al., 2024; Huang et al., 2025). These compounds have been reported in numerous studies to exhibit high antioxidant activity by donating hydrogen atoms or electrons to neutralise lipid radicals, thus interrupting the chain reaction of lipid peroxidation (Mathew and Abraham, 2006; Boulebd, 2019). However, the effectiveness of CEO as an antioxidant in lipid matrices varies widely depending on factors such as concentration, oil composition, and storage conditions (Keshvari et al., 2013). In certain systems, essential oils may even act as pro-oxidants, particularly in highly unsaturated oils, due to interactions between reactive EO components and oxygen or metal ions (de Sousa et al., 2023). Therefore, understanding the precise conditions under which the CEO operates as an antioxidant or pro-oxidant is crucial for its effective application.

While the antioxidant potential of cinnamon oil has been well documented in model emulsions and food systems, comparative studies on its stabilising effects in edible oils with distinct fatty acid profiles are still limited (Alonso et al., 2024; Ul Hasan et al., 2025). Understanding how cinnamon oil modulates oxidative stability in oils with different levels of unsaturation is critical for optimising its use as a natural preservative.

The present study, therefore, aimed to evaluate the influence of adding cinnamon essential oil on the oxidative stability of rapeseed, olive, and grapeseed oils during long-term storage. Changes in total antioxidant capacity and 2-thiobarbituric acid reactive substances were investigated as key indicators of antioxidant potential and lipid peroxidation, respectively, over 120 days of storage. It was hypothesised that the addition of CEO would enhance the antioxidant capacity of all oils and inhibit lipid oxidation, but that the magnitude and duration of these effects would differ according to oil composition and storage time. The findings are expected to provide insight into the potential use of cinnamon essential oil as a natural antioxidant for improving the shelf life and quality of edible oils. This study thus addresses a significant knowledge gap that could support the development of natural preservation strategies in the edible oil industry.

Materials and Methodology

Cinnamon Essential Oil

The commercial CEO (cinnamon essential oil) was provided by Polish essential oil manufacturers (Naturalne Aromaty sp. z o.o., Bochnia, Poland). This is a 100% natural essential oil obtained from the bark of the *Cinnamomum zeylanicum* Blume (syn. *Cinnamomum verum* J.Presl) tree through steam distillation. Samples were stored in re-sealable vials at 5 °C in the dark, but allowed to equilibrate to room

temperature before testing. Geographical origin was excluded as this information was mostly not available.

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) contains polyunsaturated fatty acids. The energy value of 100 ml is 3,404 kJ (828 kcal), fat 92 g, including 11 g of saturated fatty acids, 24 g of monounsaturated fatty acids, and 57 g of polyunsaturated fatty acids.

The rapeseed, olive, and grape seed oil samples (5 ml) were incubated with 0.1 ml CEO (final concentration 20 $\mu g \cdot mL^{-1}$) 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.

Measurement of 2-thiobarbituric Acid-reactive Substances (TBARS)

Lipid peroxidation was assessed by quantifying TBARS, primarily malondialdehyde (MDA), using the method of Buege and Aust (1978) with slight modifications. Briefly, 0.1 ml of the sample was mixed with 2.0 ml of distilled water and 2.0 ml of TBA reagent consisting of 15% trichloroacetic acid (TCA), 0.375% 2-thiobarbituric acid (TBA), and 0.25 N hydrochloric acid (HCl). The samples were then incubated in a boiling water bath at 95 °C for 15 minutes to promote the reaction between MDA and TBA, forming a pink chromogen. After incubation, the samples were cooled on ice and centrifuged at 3,000 rpm for 10 minutes to remove precipitates and clarify the solution. The absorbance of the resulting supernatant was then measured at 532 nm using a spectrophotometer. The MDA concentration, which serves as a reliable indicator of the extent of lipid peroxidation and oxidative degradation of oils, was calculated using a molar extinction coefficient of 1.56×10^5 $M^{-1} \cdot cm^{-1}$. This method is sensitive and widely accepted for monitoring lipid oxidation in food and biological samples.

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 (Opryshko et al., 2021). The sample inhibits the Fe^{2+}/ascorbate-induced oxidation of Tween 80, resulting in a decrease in the TBARS level. The amount of TAC in the sample (%) was calculated from the absorbance of the blank.

Statistical Analysis

Results are expressed as means. 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 v. 13.3 software (TIBCO Software Inc., Palo Alto, USA).

Results and Discussion

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 (TAC) of rapeseed oil decreased progressively during storage. Compared to the initial value on day 0, the TAC of the control sample decreased by 13.38% ($p > 0.05$), 15.73% ($p > 0.05$), 51.19% ($p < 0.05$), 45.97% ($p < 0.05$) and 19.41% ($p > 0.05$) after 7, 15, 30, 60 and 120 days, respectively. In rapeseed oil supplemented with cinnamon essential oil (Cinnamon EO + RO), the TAC decreased by 2.28% ($p > 0.05$), 11.27% ($p > 0.05$), 24.55% ($p < 0.05$), 49.94% ($p < 0.05$), and 5.47% ($p > 0.05$) over the same storage periods. Adding cinnamon EO to rapeseed oil significantly improved its antioxidant stability after 30 and 120 days of storage, with TAC values 45.70% ($p < 0.05$) and 10.56% ($p < 0.05$) higher than the control, respectively. A slight, non-significant increase in TAC levels was also observed at 7 and 15 days in cinnamon EO-enriched samples, by 6.35% ($p > 0.05$) and 0.69% ($p > 0.05$) respectively (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 TAC of olive oil decreased during storage. Compared to the initial value (0 day), the TAC of control olive oil decreased by 14.39% (p >0.05), 25.23% (p >0.05), 32.93% (p <0.05), 32.52% (p <0.05), and 19.93% (p >0.05) after 7, 15, 30, 60, and 120 days of storage, respectively. In olive oil supplemented with cinnamon essential oil (Cinnamon EO + OO), the TAC was reduced by 8.64% (p > 0.05), 19.54% (p <0.05), 15.97% (p <0.05), 32.95% (p <0.05), and 7.42% (p >0.05) over the same storage periods. The addition of cinnamon EO to olive oil increased the TAC values at 30 and 120 days of storage by 11.06% (p <0.05) and 19.17% (p <0.05),

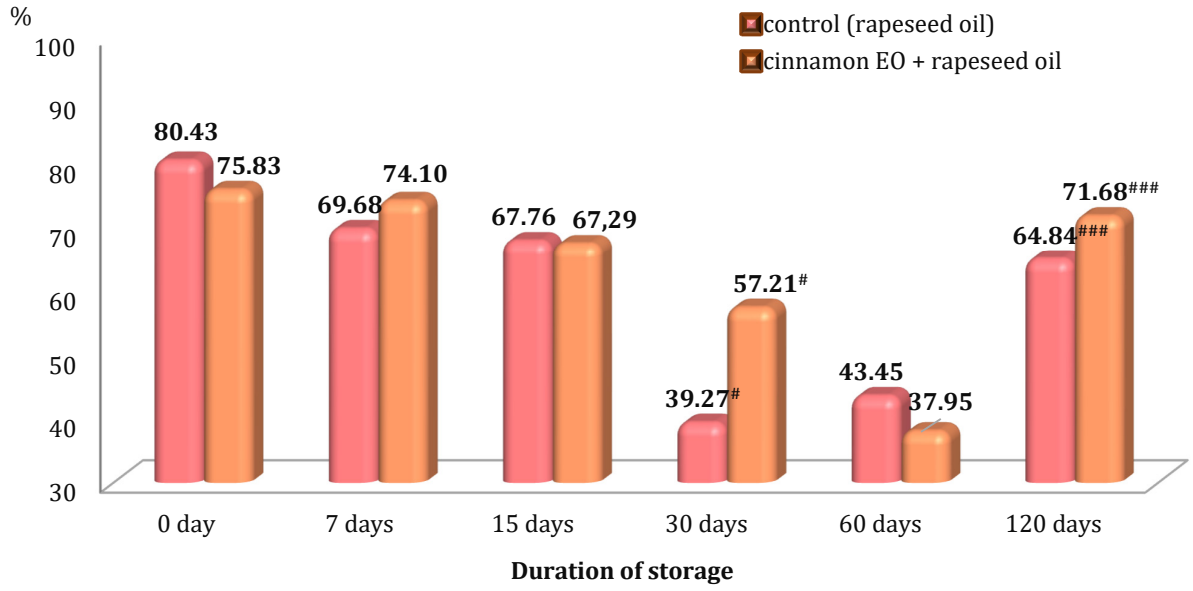

Figure 1 Effect of CEO addition and storage time on the total antioxidant capacity (TAC, %) of rapeseed oil after 7, 15, 30, 60, and 120 days of storage
changes significantly different between the control (rapeseed oil) and the CEO addition after 30 days of storage (p <0.05, n = 6); ### changes significantly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

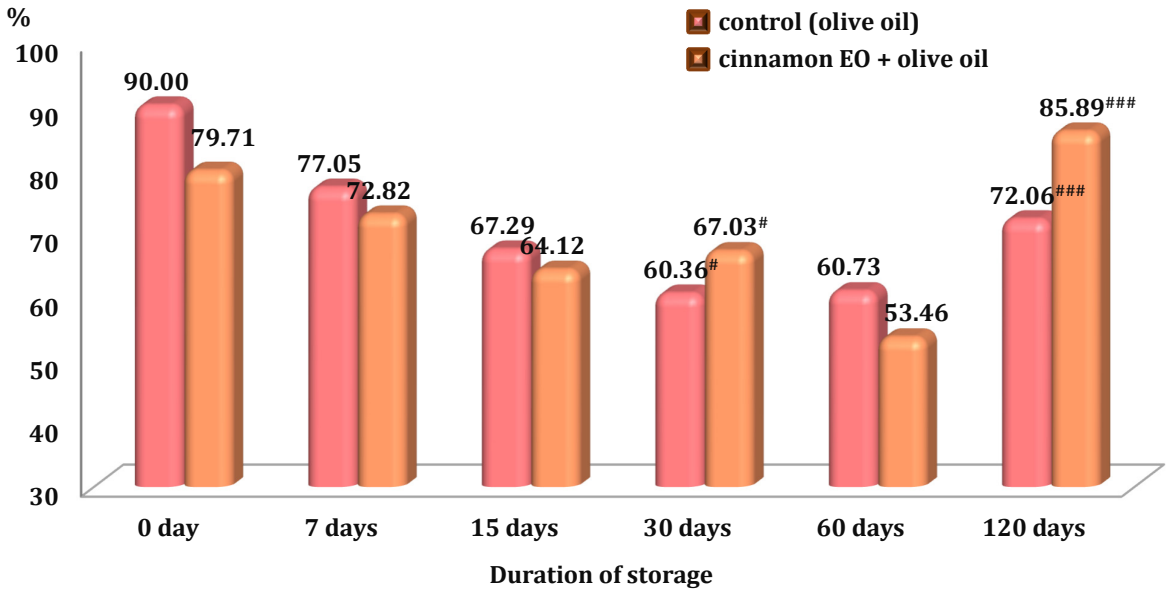

Figure 2 Effect of GEO addition and storage time on the total antioxidant capacity (TAC, %) of olive oil after 7, 15, 30, 60 and 120 days of storage
changes significantly different between the control (olive oil) and the CEO addition after 30 days of storage (p <0.05, n = 6); ### changes significantly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

respectively, compared to the control samples. At 7 and 15 days, a slight, non-significant increase in TAC levels was also observed in the cinnamon EO-enriched samples compared to the control, by 2.22% ($p > 0.05$) and 1.39% ($p > 0.05$), respectively (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 TAC of grapeseed oil gradually decreased during storage. Compared to the initial value (0 day), the TAC of control grapeseed oil decreased by 6.21% ($p > 0.05$), 12.90% ($p > 0.05$), 19.38% ($p < 0.05$), 22.36% ($p < 0.05$), and 14.27% ($p > 0.05$) after 7, 15, 30, 60, and 120 days of storage, respectively. In grapeseed oil supplemented with cinnamon essential oil (Cinnamon EO + GSO), the TAC was reduced by 4.57% ($p > 0.05$), 10.05% ($p > 0.05$), 14.00% ($p < 0.05$), and 24.28% ($p < 0.05$) after 7, 15, 30, and 60 days, but increased by 2.73% ($p > 0.05$) after 120 days of storage, compared to the initial value. The addition of cinnamon EO to grapeseed oil significantly improved the TAC at 7, 15, and 120 days of storage by 6.56% ($p < 0.05$), 7.52% ($p < 0.05$), and 13.78% ($p < 0.05$), respectively, compared to the control. A minor, non-significant increase (1.33%; $p > 0.05$) was also noted at 30 days, whereas a slight decrease (7.30%; $p > 0.05$) occurred after 60 days (Figure 3).

The effect of CEO addition and storage time on the TBARS level as a marker of lipid peroxidation of rapeseed, olive, and grapeseed oils at 7, 15, 30, 60, and 120 days of storage is shown in Figures 4–6.

The TBARS content, used as an indicator of lipid peroxidation, increased progressively during the storage of rapeseed oil. In the control samples, the TBARS level rose sharply from 2.56 at day 0 to 4.89, 16.67, 36.79, 45.51, and 112.82 nmol MDA·mL^{-1} after 7, 15, 30, 60, and 120 days of storage, respectively, corresponding to increases of 90.82% ($p < 0.05$), 551.17% ($p < 0.05$), 1,336.33% ($p < 0.05$), 1,677.73% ($p < 0.05$), and 4,307.03% ($p < 0.05$) compared to the initial value. In rapeseed oil enriched with cinnamon essential oil (Cinnamon EO + RO), TBARS values were markedly higher than those in the control during the early storage period. The TBARS content increased from 22.31 nmol MDA·mL^{-1} at day 0 to 21.26, 32.56, 46.41, 37.18, and 148.72 nmol MDA·mL^{-1} after 7, 15, 30, 60, and 120 days, corresponding to variations of -4.72% ($p > 0.05$), +46.00% ($p < 0.05$), +108.01% ($p < 0.05$), +66.67% ($p < 0.05$), and +566.68% ($p < 0.05$), respectively, relative to the initial value. Although cinnamon EO supplementation did not suppress lipid oxidation at the beginning of storage, a slower increase in TBARS was observed in the enriched samples compared to the control at 60 days (-18.31%, $p < 0.05$). However, at the final stage (120 days), TBARS levels

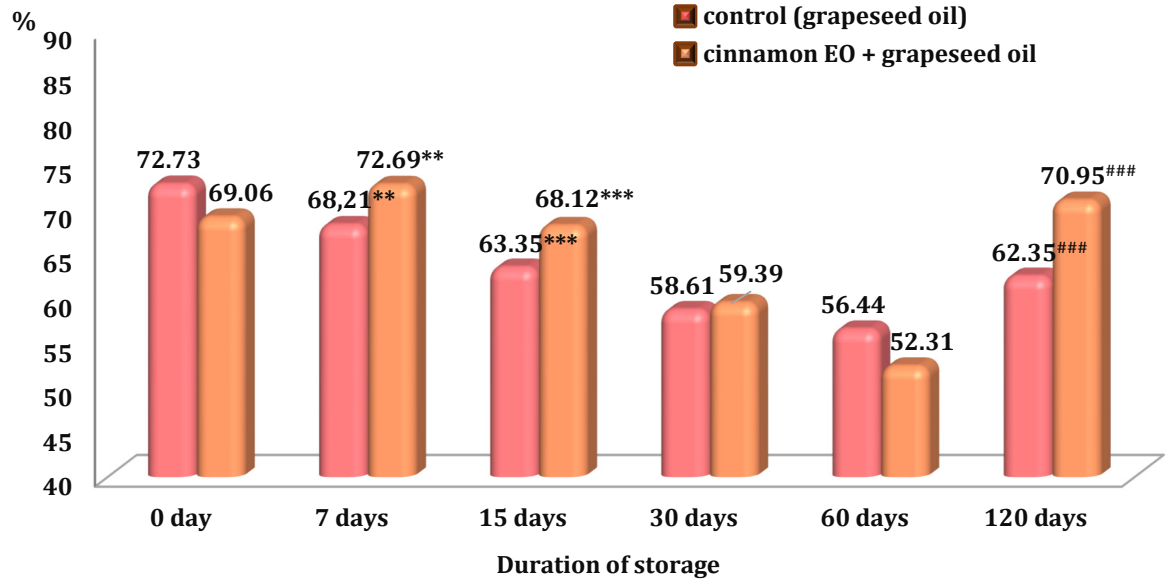

Figure 3 Effect of CEO addition and storage time on total antioxidant capacity (TAC, %) in grapeseed oil after 7, 15, 30, 60 and 120 days of storage
** changes significantly different between the control (grapeseed oil) and the CEO addition after 7 days of storage ($p < 0.05$, n = 6); *** changes significantly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

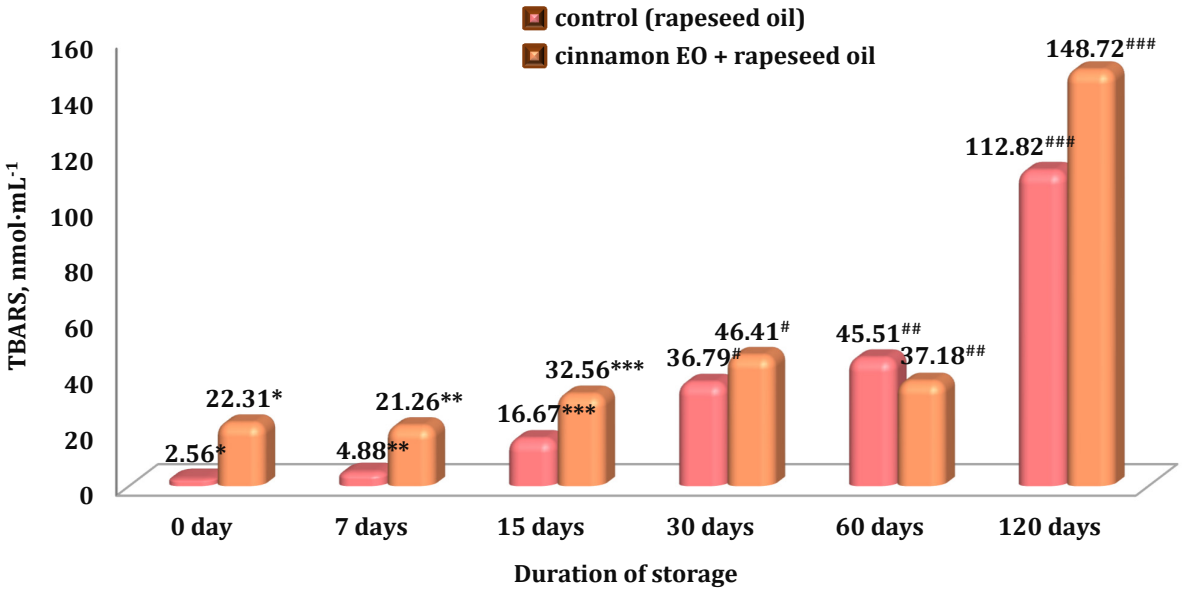

Figure 4 Effect of CEO addition and storage time on the TBARS level of rapeseed oil after 7, 15, 30, 60, and 120 days of storage

* changes were significantly different between the control (rapeseed oil) and the CEO addition on day 0 of storage ($p < 0.05$, $n = 6$); ** changes were significantly different between the control (rapeseed oil) and the CEO addition after 7 days of storage ($p < 0.05$, $n = 6$); *** changes were significantly different between the control (rapeseed oil) and the CEO addition after 15 days of storage ($p < 0.05$, $n = 6$); # changes were significantly different between the control (rapeseed oil) and the CEO addition after 30 days of storage ($p < 0.05$, $n = 6$); ## changes were significantly different between the control (rapeseed oil) and the CEO addition after 60 days of storage ($p < 0.05$, $n = 6$); ### changes were significantly different between the control (rapeseed oil) and the CEO addition after 120 days of storage ($p < 0.05$, $n = 6$)

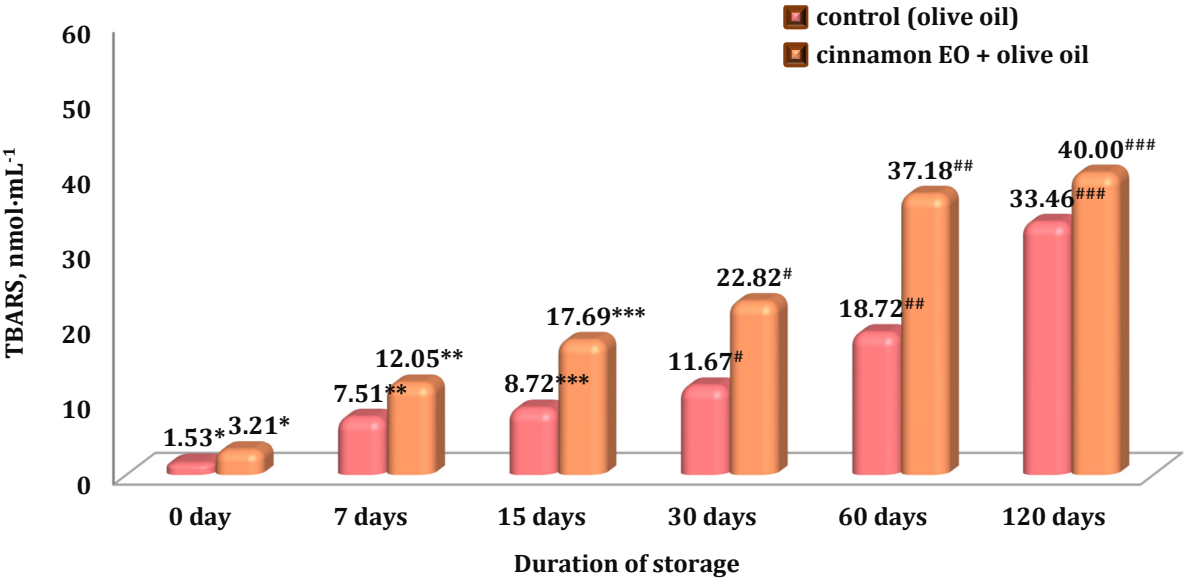

Figure 5 Effect of CEO addition and storage time on the TBARS level of olive oil after 7, 15, 30, 60, and 120 days of storage

* changes were significantly different between the control (olive oil) and the CEO addition on day 0 of storage ($p < 0.05$, $n = 6$); ** changes were significantly different between the control (olive oil) and the CEO addition after 7 days of storage ($p < 0.05$, $n = 6$); *** changes were significantly different between the control (olive oil) and the CEO addition after 15 days of storage ($p < 0.05$, $n = 6$); # changes were significantly different between the control (olive oil) and the CEO addition after 30 days of storage ($p < 0.05$, $n = 6$); ## changes were significantly different between the control (olive oil) and the CEO addition after 60 days of storage ($p < 0.05$, $n = 6$); ### changes were significantly different between the control (olive oil) and the CEO addition after 120 days of storage ($p < 0.05$, $n = 6$)

in the Cinnamon EO + RO group were significantly higher (+31.82%, p <0.05) than in the control, indicating pro-oxidative changes during prolonged storage (Figure 4).

The TBARS level of olive oil after addition of CEO at 7, 15, 30, 60, and 120 days of storage is shown in Figure 5.

The TAC of olive oil decreased during storage. Compared to the initial value (0 day), the TAC of control olive oil decreased by 14.39% (p >0.05), 25.23% (p >0.05), 32.93% (p <0.05), 32.52% (p <0.05), and 19.93% (p >0.05) after 7, 15, 30, 60, and 120 days of storage, respectively. In olive oil supplemented with cinnamon essential oil (Cinnamon EO + OO), the TAC was reduced by 8.64% (p >0.05), 19.54% (p <0.05), 15.97% (p <0.05), 32.95% (p <0.05), and 7.42% (p >0.05) over the same storage periods. The addition of cinnamon EO to olive oil increased the TAC values at 30 and 120 days of storage by 11.06% (p <0.05) and 19.17% (p <0.05), respectively, compared to the control samples. At 7 and 15 days, a slight, non-significant increase in TAC levels was also observed in the cinnamon EO-enriched samples compared to the control, by 2.22% (p >0.05) and 1.39% (p >0.05), respectively (Figure 2).

The TBARS levels of grapeseed oil after addition of CEO at 7, 15, 30, 60, and 120 days of storage are shown in Figure 6.

The formation of TBARS was used to evaluate lipid peroxidation in grapeseed oil during storage. In the control samples, TBARS levels increased steadily from 1.24 nmol MDA·mL^{-1} at day 0 to 3.21, 4.36, 16.16, 31.15, and 43.85 nmol MDA·mL^{-1} after 7, 15, 30, 60, and 120 days of storage, respectively. These values represent increases of 158.87% (p <0.05), 251.61% (p <0.05), 1203.23% (p <0.05), 2411.29% (p <0.05), and 3436.29% (p <0.05) compared to the initial value. In grapeseed oil enriched with cinnamon essential oil (Cinnamon EO + GSO), TBARS values rose from 3.00 nmol MDA·mL^{-1} at day 0 to 15.38, 16.67, 22.82, 19.74, and 43.59 nmol MDA·mL^{-1} after 7, 15, 30, 60, and 120 days, corresponding to increases of 412.67% (p <0.05), 455.67% (p <0.05), 660.67% (p <0.05), 558.00% (p <0.05), and 1353.00% (p <0.05), respectively, relative to the initial value. The addition of cinnamon EO intensified lipid peroxidation throughout most of the storage period. TBARS levels in the Cinnamon EO + GSO samples were higher than in the control by 379.44% (p <0.05), 282.34% (p <0.05), 41.23% (p <0.05), and 18.09% (p >0.05) after 7, 15, 30, and 120 days, respectively. Only at 60 days was a lower TBARS concentration observed in the enriched samples (-36.61%, p <0.05), suggesting a transient antioxidative effect (Figure 6).

This study examined the effect of the CEO on the oxidative stability of rapeseed, olive, and grape seed oils over a long storage period, as measured by total antioxidant capacity (TAC) and lipid peroxidation (TBARS levels). The results clearly demonstrate

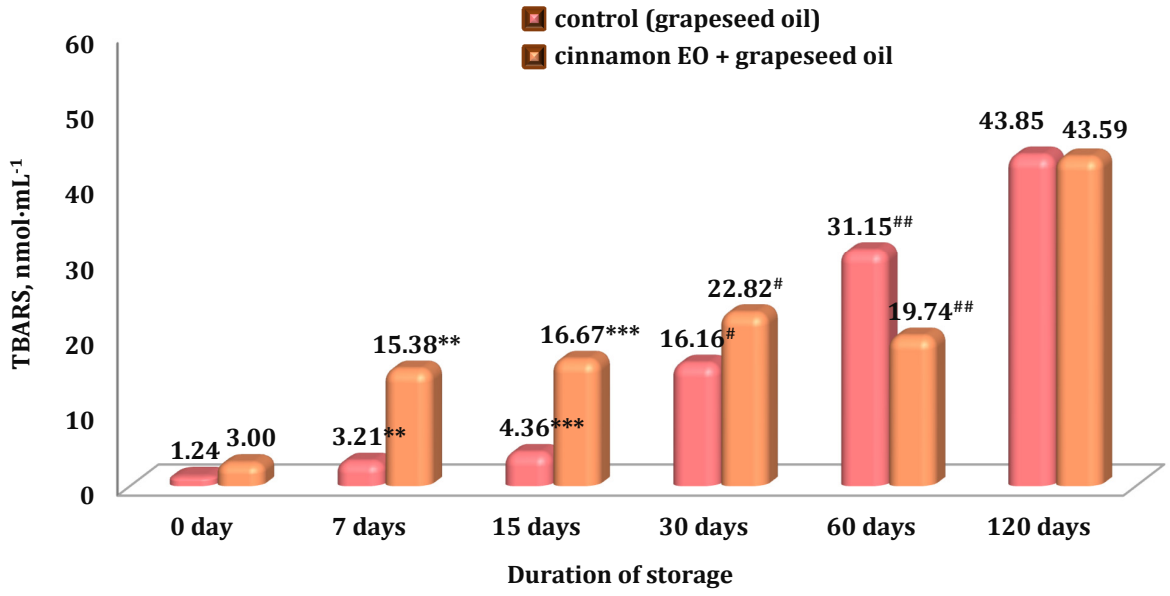

Figure 6 Effect of CEO addition and storage time on TBARS levels in grapeseed oil after 7, 15, 30, 60, and 120 days of storage
** changes were significantly different between the control (grapeseed oil) and the CEO addition after 7 days of storage (p <0.05, n = 6); *** changes were significantly different between the control (grapeseed oil) and the CEO addition after 15 days of storage (p <0.05, n = 6); # changes were significantly different between the control (grapeseed oil) and the CEO addition after 30 days of storage (p <0.05, n = 6); ## changes were significantly different between the control (grapeseed oil) and the CEO addition after 60 days of storage (p <0.05, n = 6)

that storage time markedly affects both antioxidant capacity and oxidative degradation in all oils tested, while the impact of CEO addition varies depending on the type of oil and the duration of storage. In all control samples, TAC decreased progressively during storage, confirming the gradual depletion of intrinsic antioxidants, such as tocopherols, phenolic compounds, and carotenoids (Li et al., 2025). However, the rate of decline differed among oils, reflecting their distinct fatty acid compositions and natural antioxidant profiles. Rapeseed and grapeseed oils, which contain higher levels of polyunsaturated fatty acids (PUFAs), showed faster loss of antioxidant activity than olive oil, which contains more monounsaturated oleic acid and phenolic constituents (Yun and Surh, 2012; Loganathan et al., 2022).

Supplementing with CEO reduced the loss of TAC in all oils, particularly after 30 and 120 days of storage. The enhancement of TAC levels reached 45.7 and 19.17% in rapeseed and olive oils, respectively, compared to the control. This suggests that the CEO contributes additional radical-scavenging capacity and acts synergistically with the oils' native antioxidants. These results are consistent with previous reports indicating that cinnamon oil, which is rich in cinnamaldehyde, eugenol, and coumarin, exhibits potent electron-donating and hydrogen-transfer abilities that can inhibit lipid oxidation chain reactions (Rao and Gan, 2014; Dorri et al., 2018).

However, in grapeseed oil, CEO supplementation primarily improved TAC at the early (7–15 days) and late (120 days) stages of storage, but not in the mid-storage period. This inconsistency may reflect the complex interactions between CEO components and the high polyunsaturated fatty acid (PUFA) content of grapeseed oil, which makes it more prone to oxidation and may facilitate the transformation of some CEO constituents into less active forms under oxidative stress (Kalemba and Kunicka, 2003; Kong et al., 2022).

TBARS values increased markedly in all control oils during storage, indicating progressive lipid peroxidation and the formation of secondary oxidation products, such as malondialdehyde (MDA). As expected, oils with higher levels of PUFAs exhibited the most pronounced increase in TBARS values, with grapeseed oil showing an increase of over 3400% after 120 days. Olive oil showed the lowest TBARS accumulation, confirming its superior oxidative stability (Farhoosh et al., 2014; Benguennouna et al., 2025).

The effect of CEO addition on TBARS formation depended strongly on both oil type and storage duration. In the early storage stages (0–30 days), CEO-enriched oils, especially rapeseed and grapeseed oils, exhibited unexpectedly higher TBARS levels than the control oils. This suggests a transient pro-oxidant effect of cinnamon oil, possibly due to its high cinnamaldehyde content, which can react with oxygen or metal ions to form reactive intermediates under certain conditions (Yanishlieva et al., 2006; Yu et al., 2020). However, at the intermediate storage time of 60 days, the addition of CEO appeared to suppress lipid oxidation in rapeseed and grapeseed oils, as evidenced by TBARS levels that were 18.3 and 36.6% lower, respectively, than those of the controls. This biphasic behaviour – initial pro-oxidation followed by antioxidation – has also been observed in other essential oil-enriched lipid systems (Bakkali et al., 2008; Abril et al., 2019).

At the final stage of storage (120 days), divergent trends emerged. In the case of rapeseed oil, the CEO-enriched samples exhibited higher TBARS values than the controls, suggesting that the essential oil's antioxidant components had either been depleted or had been transformed into pro-oxidant derivatives. By contrast, olive oil maintained relatively low TBARS values, suggesting that its endogenous phenolic compounds and monounsaturated fatty acid content provided a stabilising environment that allowed the CEO components to remain active for longer. Grapeseed oil exhibited intermediate behaviour, with CEO-induced enhancement of peroxidation in the early stages, followed by partial protection after prolonged storage.

The observed differences in CEO efficacy among the oils likely stem from chemical and matrix-related factors. The polarity and solubility of essential oil compounds influence their distribution between lipid and interfacial phases, thereby affecting their antioxidant efficiency (Frankel et al., 1994; Laguerre et al., 2015). Olive oil, with its higher viscosity and lower PUFA content, may provide a more stable medium for the retention and gradual release of CEO constituents. Conversely, the higher unsaturation and oxidative susceptibility of rapeseed and grapeseed oils may accelerate the degradation of cinnamaldehyde and other phenylpropanoids, thereby reducing their long-term antioxidant effectiveness (Stevanović et al., 2018). Furthermore, the antioxidant activity of essential oils depends on concentration; excessive doses may disrupt the redox balance and exhibit pro-oxidant behaviour (Ruberto and Baratta, 2000). Therefore, optimising CEO concentration is crucial to maximising protection while avoiding oxidative instability.

Numerous studies have confirmed that CEO effectively extends the shelf life of perishable food products, including fruits, vegetables, meat, and dairy, by inhibiting microbial growth and lipid oxidation while maintaining desirable sensory characteristics such as colour and aroma (Mao et al., 2024; Zhou et al., 2025). The phenolic and aldehydic components of CEO, particularly cinnamaldehyde and eugenol, are responsible for its antimicrobial and antioxidant properties, which slow down enzymatic browning and oxidative spoilage in fresh produce (Rao and Gan, 2014). However, CEO's intrinsic physicochemical properties – namely their high volatility, limited water solubility, and strong, pungent odour – pose significant challenges to their direct incorporation into food systems. Volatile losses through evaporation diminish its antimicrobial efficacy, while excessive local concentrations may penetrate porous or odour-absorbent food matrices, altering their sensory profiles (Marsin et al., 2020). For example, bakery products packaged with CEO-enriched materials may acquire a distinct cinnamon taste if release kinetics are not controlled properly (Balaguer et al., 2013), and the migration of cinnamaldehyde into dairy products has been shown to give them an unpleasant spicy flavour (Ali et al., 2021). These sensory alterations can reduce consumer acceptability and limit the practical application of CEO as a direct food preservative.

To overcome these limitations, recent research has focused on developing advanced encapsulation and delivery systems that protect the CEO from premature degradation and enable controlled release in food packaging environments (Luo et al., 2024). Microencapsulation has proven particularly effective in this regard: by entrapping the CEO within a protective wall composed of biopolymers such as chitosan, maltodextrin, or gum arabic, it is possible to modulate its diffusion rate and release pattern. This minimises odour interference while maintaining antimicrobial potency (Huang et al., 2022). Such microcapsules also improve the thermal stability of CEO and its resistance to oxidative degradation, which are essential for its integration into heat-processed packaging materials.

Similarly, nanoemulsion-based systems (NEs) have emerged as another promising technology for enhancing CEO stability and bioavailability. By tailoring the type and concentration of surfactants and controlling droplet size, the volatility of these systems can be reduced and aroma loss during storage can be prevented (Liang et al., 2022; Zhang et al., 2023). For instance, Chuesiang et al. (2021) showed that Asian sea bass fillets stored under refrigeration and treated with 11,429 mg·L^{-1} of CEO nanoemulsions experienced a reduction in initial bacterial counts of 0.5–1.5 log CFU·g^{-1} compared to untreated controls. The nanoemulsion inhibited the proliferation of spoilage bacteria, including *Vibrio parahaemolyticus*, more efficiently than bulk CEO or sodium hypochlorite, confirming its enhanced antimicrobial stability during cold storage (4 ±2 °C). These findings highlight the importance of nanoscale structuring in improving the dispersion, efficacy, and retention of CEO in the lipid and aqueous phases of food matrices (Chuesiang et al., 2021).

Recent studies have emphasised the promising antimicrobial properties of CEO in biodegradable food packaging systems (Lucas-González et al., 2023). Derived from the bark and leaves of *Cinnamomum* species, CEO contains key bioactive constituents such as cinnamaldehyde, cinnamic acid, and cinnamate, which exhibit strong antibacterial and antifungal properties. These compounds combat both spoilage microorganisms and foodborne pathogens, making CEO an ideal candidate for extending the shelf life of perishable food products. According to Lucas-González et al. (2023), incorporating CEO into biodegradable films, edible coatings, and adhesive patches imparts antimicrobial protection and enhances the barrier, thermal, and mechanical properties of packaging materials. This dual functionality improves the safety and physical performance of packaging. However, the study emphasises that the efficiency of CEO-based systems critically depends on maintaining an optimal balance between the retention and controlled release of the oil's volatile components.

Thus, the data obtained in this study confirm that cinnamon essential oil can enhance the antioxidant potential of edible oils, although its stabilising effect is strongly dependent on the matrix and time (Shahid et al., 2018; Mahdi et al., 2021). In olive oil, CEO supplementation demonstrated the most consistent protective effect, suggesting its potential as a natural preservative for oils with medium oxidative stability. In contrast, the inconsistent results obtained with rapeseed and grapeseed oils suggest that the use of CEO in highly unsaturated matrices requires careful formulation, possibly in combination with other antioxidants (e.g., tocopherols or rosemary extract), to prevent pro-oxidant effects during long-term storage.

From a food industry perspective, integrating CEO as a natural antioxidant would align with the growing demand for clean-label products with reduced synthetic additives. However, further studies are needed to explore the optimal concentration of CEO, its encapsulation methods, and its interactions with

minor oil components, in order to ensure consistent oxidative stability during extended storage and under variable environmental conditions.

Conclusions

This study demonstrated that the storage duration has a strong impact on the oxidative stability of edible oils and that the effect of adding CEO varies depending on the oil type and storage time. In rapeseed and olive oils, CEO supplementation significantly enhanced antioxidant capacity, particularly after prolonged storage (30–120 days), indicating a protective effect against oxidative degradation. In contrast, grapeseed oil, which is characterised by a high polyunsaturated fatty acid content, exhibited inconsistent responses: transient pro-oxidant effects in the early stages and moderate antioxidant protection in the later stages. These findings emphasise that the oxidative behaviour of CEO depends not only on its intrinsic radical-scavenging properties, but also on its interaction with the lipid matrix and storage environment. From a practical perspective, cinnamon essential oil can be considered a promising natural antioxidant additive for improving the oxidative stability of edible oils, particularly those with moderate levels of unsaturation, such as olive and rapeseed oils. However, its concentration and formulation must be carefully optimised to avoid potential pro-oxidative interactions in highly unsaturated oils. Future research should focus on elucidating the mechanisms of CEO-lipid interactions, evaluating synergistic combinations with other natural antioxidants, and assessing sensory and physicochemical stability under real storage and processing conditions. Thus, the results support the potential use of cinnamon essential oil as a natural, clean-label antioxidant in the food industry, offering an effective, consumer-friendly alternative to synthetic preservatives for extending the shelf life of edible oils.

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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