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Research article

EFFECT OF *Coriandrum sativum* L. EXTRACTS ON THE OXIDATIVE STABILITY OF COLD-PRESSED SUNFLOWER OIL

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Aleksandra Stojićević[1*], Biljana Rabrenović[2], Ana Alimpić Aradski[3], Mališa Antić[2], Darko Micić[4], Miloš Purić[1]

[1]The Academy of Applied Studies Polytechnic, Katarine Ambrozić 3, 11050 Belgrade, Serbia
[2]University of Belgrade, Faculty of Agriculture, Nemanjina 6, 11080, Belgrade- Zemun, Serbia
[3]University of Belgrade, Faculty of Biology, Institute of Botany and Botanical Garden „Jevremovac", Studentski trg 16, 11000 Belgrade, Serbia
[4]Institute of General and Physical Chemistry, Studentski trg 12/V, Belgrade 11158, Serbia
**Corresponding author*: astojicevic@politehnika.edu.rs

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ABSTRACT

One of the most important quality parameters of edible vegetable oils is their oxidation stability, especially when their chemical composition is dominated by polyunsaturated fatty acids, which are susceptible to oxidation. Even under optimal storage conditions, these oils have a limited shelf life. Given the harmful effects of synthetic antioxidants, increasing attention has been directed towards natural antioxidants in efforts to delay oxidative changes in edible oils. Medicinal and aromatic plants are used worldwide as food ingredients, flavouring agents and sources of promising antioxidants. In this context, the main objective of this study was to evaluate the effect of ethanolic extracts obtained from coriander seeds on the oxidative stability of cold-pressed sunflower oil (CPSO). The preliminary tests focused on evaluating the influence of the extraction conditions (extraction technique and solvent type) on the antioxidant activity of the coriander extracts. Regardless of the extraction technique employed, 70% ethanolic extracts showed a stronger antioxidant effect compared to 96% extracts, which is why 70% ethanolic extracts were selected for further analyses. These extracts were added to fresh CPSO at different concentrations (250, 500 and 1000 ppm) and their stabilising effects were monitored using accelerated techniques (Schaal oven and Rancimat test). While the lower concentrations of coriander extract showed certain capacity to delay oxidative changes, the highest concentration acted as a pro-oxidant.

Key words:
oxidative stability, medicinal and aromatic plants, coriander, cold-pressed sunflower oil, ethanolic extracts

Abbreviations:
CPSO – cold-pressed sunflower oil; CPO – cold-pressed oil; SE – Soxhlet extraction; UAM – ultrasound-assisted maceration; *β*-CB – *β*-carotene bleaching assay; PV – peroxide value; AV – *p*-anisidine value; CD – conjugated dienes; CT – conjugated trienes; BHA – butylated hydroxyanisole; BHT- butylated hydroxytoluene; $CPSO_{BHT}$ – CPSO sample with an addition of BHT; $CPSO_0$ – CPSO sample without additives; IP – induction period; $SE_{70\%}$ – extract obtained using SE and 70% ethanol; $SE_{96\%}$ – extract obtained using SE and 96% ethanol; $UAM_{70\%}$ – extract obtained using UAM and 70% ethanol; $UAM_{96\%}$ – extract obtained using UAM and 96% ethanol

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INTRODUCTION

In recent years, interest in less processed products, such as cold-pressed oils (CPOs), has grown significantly. In this regard, cold pressing is becoming increasingly important as a method of oil extraction. CPOs are extracted mechanically and purified only by physical processes (Rulebook, 2013). Compared to refined oils, CPOs retain higher contents of bioactive substances, which are eliminated during refining processes (Rabiej-Kozioł et al., 2023). The shelf life, nutritional value and functional properties of CPOs largely depend on their chemical composition, especially the fatty acid composition. The presence of minor components is also essential for maintaining oil stability and delaying oxidation. On the other hand, due to minimal processing, fresh CPOs have a higher content of pro-oxidant components (oxidation products, free fatty acids, traces of metals, pigments, etc.). Considering all of these factors and given the legal prohibition of adding synthetic antioxidants to CPOs, stabilizing the oils with such complex compositions is a particular challenge. Among the various methods developed to delay oxidative changes, the use of plant antioxidants is one of the most common methods (Kiralan et al., 2017). Herbs are a rich natural source of antioxidants and have the potential to delay oxidative changes in oils. The effectiveness of their application depends on many factors, including the specific part of the plant used, the extraction conditions and the concentration of the extract added to the oil. One of the most important steps is selecting an appropriate technique and optimal extraction conditions to isolate active ingredients. Conventional techniques, such as Soxhlet extraction and maceration, have certain limitations including high solvent and time consumption. In addition, the Soxhlet method requires high temperatures, which can lead to the thermal decomposition of thermolabile compounds (Zhang et al., 2018). On the other hand, increased temperature can reduce viscosity of the solvent, allowing it to penetrate into the plant matrix more easily, resulting in faster extraction and higher yields (Miron et al., 2011). The disadvantages of maceration can be overcome by using ultrasound. The application of ultrasonic waves leads to the release of the target compounds, so ultrasound-assisted maceration achieves higher extraction efficiency compared to conventional maceration (Alimpić et al., 2015). In solvent extraction, the choice of solvent is crucial (Zhang et al., 2018). The properties of a good solvent for herbal extraction include low toxicity, easy evaporation, inability to cause the extract to form complexes and a preservative effect. Commonly used solvents include methanol, ethanol, water and their mixtures as well as ethyl acetate and acetone (Bucić-Kojić et al., 2011). Binary solvent systems, such as a mixture of water and ethanol, provide higher yields of biactive compounds compared to mono-component solvents (Spigno et al., 2007; Ćujić et al., 2016; Jovanović et al., 2017). Furthermore, from a toxicological perspective, ethanol and water are more suitable for applications in the food industry compared to other organic solvents (Bucić-Kojić et al., 2011).
Plants from the Apiaceae family are commonly used as dietary supplements and natural preservatives (Aćimović et al., 2017). Among them, coriander (*Coriandrum sativum* L.) is an annual plant native to Arabian Peninsula, Western Asia and Indian subcontinent (Pakistan), now intensively cultivated worldwide (WFO, 2025). Although all parts of the plant are used (including fruits, stems, leaves and roots), coriander seeds and the essential oil extracted from them are the most commonly used. The medicinal properties and nutritional importance of coriander seeds are attributed to a range of bioactive compounds, including essential oil components (linalool, γ-terpinene, *p*-cimene, limonene, α-pinene, camphor). The seeds also contain 12-25% of lipids, mainly composed of petroselinic acid (Aćimović, 2014; Iqbal et al., 2018). Rajeshwari and Andallu (2012) reported that ethanolic extracts of coriander seed are rich in flavonoids such as rutin, chlorogenic acid, caffeic acid and quercetin. In traditional medicine, coriander is used to treat the digestive disorders, prevent cramps and flatulence and stimulate digestive enzyme secretion. In addition, it is used as a spice, preservative or auxiliary agent in the production of spirits, beverages, marinades, sauces, pickles, chewing gum and in various baked, meat and confectionery products (Aćimović, 2014). Previous studies investigating the impact of coriander on the oxidation stability of edible oils showed different results (Table 1).
To the date, no studies have comprehensively examined the influence of selected extraction techniques and solvents on the antioxidant capacity of coriander seed extracts, nor have they investigated how such extracts affect the oxidative stability of cold-pressed sunflower oil (CPSO) under accelerated storage conditions. Accordingly, this study aimed to examine the influence of extraction technique (Soxhlet extraction, SE and ultrasound-assisted maceration, UAM) and solvent type (70 and 96% ethanol) on the antioxidant activity of coriander extracts. Based on the results obtained using the β-carotene bleaching assay (β-CB), coriander extracts with the highest antioxidant capacity were selected for evaluation of CPSO oxidative stability with the addition of selected extracts in accelerated stability tests (Schaal oven and Rancimat).

Table 1. Previous studies on application of coriander for oxidative stabilization of edible oils

Type of edible oil	Coriander sample	Oxidative stability test	Concentration used	Reference
crude soybean oil	ethanolic extract of coriander seeds	Rancimat Pressurized differential scanning calorimetry (PDSC)	1000 mg/kg	Cordeiro et al., (2013)
refined sunflower oil	essential oil from stems and leaves	accelerated storage (65 °C)	300, 600 and 1200 mg/kg	Wang et al., (2018)
refined rapeseed oil	essential oil	heating cycles in a fryer from room temperature to 180 °C	10 mg/kg	Sghaier et al. (2017)
crude sunflower oil	ethanolic extracts of seed and green parts of coriander	accelerated storage (60 °C)	100 mg/kg	Farah et al., (2015)
cold-pressed pumpkin seed oil	essential oil	accelerated storage (70 °C)	200 and 400 mg/kg	Aćimović et al., (2017)
refined sunflower oil	aqueous extracts of stem and leaves	Rancimat	1600 mg/kg	Angelo and Jorge (2008)
sunflower oil	essential oil	Rancimat and Oxitest	0.0002%	Tinello et al., (2018)

MATERIAL AND METHODS

Plant material and edible oil sample

Dried coriander seeds (*Coriandrum sativum* L.) were obtained from the Institute for Medicinal Plant Research "Dr. Josif Pančić" Belgrade, Serbia, in 2016 (serial number 04920216). Immediately before the extraction process, the plant material was ground into powder using a laboratory electric mill. CPSO was obtained from Uvita D.O.O. (Debeljača, Serbia) and stored in its original packaging in the dark prior to analysis.

Preparation of coriander extracts

Two extraction techniques, SE (Soxhlet extraction) and UAM (ultrasound-assisted maceration), were employed using 70 and 96% ethanol. For SE, the ground plant material (10 g) was continuously extracted in a Soxhlet apparatus for 7 hours with 100 ml of extraction solvent. For UAM, the 10 g of the plant material was extracted with an extraction solvent (100 ml) by classical maceration for 24 hours at room temperature. Ultrasonic treatment was applied in the first and last hour of the extraction process using an ultrasonic bath. In addition, the liquid extracts were filtered through a filter paper (Whatman No. 1) and the solvent was evaporated under reduced pressure using a rotary evaporator at a maximum temperature of 40 °C. The obtained crude extracts were stored at 4 °C until further analysis. For the assessment of the antioxidant activity, dry extracts were dissolved in an appropriate solvent to obtain a final concentration of 0.1 mg/ml.

Antioxidant activity of coriander extracts

Antioxidant activity was evaluated using the β-CB assay, following a modified version of the method described by Dapkevicius et al. (1998). A β-carotene/linoleic acid emulsion was prepared by dissolving β-carotene (5 mg), linoleic acid (12.5 µl) and Tween 40 (100 mg) in 1 ml of chloroform. The chloroform was evaporated from the emulsion using a rotary vacuum evaporator at 40 °C, and the dry residue was dissolved in 50 ml of distilled water. The emulsion (500 µl) was mixed with 0.1 mg/ml ethanolic solution of the coriander extracts (70 µl). The control sample was prepared in the same manner, except ethanol was used instead of the coriander extract. Absorbance of the control sample was measured at 490 nm immediately and then after 120 minutes of incubation, while the absorbance of the extract samples and standards was measured only after 120 minutes of incubation. Distilled water served as a blank, while 0.1 mg/ml solutions of butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) were separately used as positive controls. The percentage of inhibition of β-carotene oxidative degradation was calculated using the following Formula 1:

$$\%\ of\ inhibition = \frac{A_{120} - C_{120}}{C_0 - C_{120}} \times 100 \qquad \text{(Formula 1)}$$

where:
A_{120} – absorbance of the extract sample measured after 120 minutes of incubation
C_{120} – absorbance of the control sample measured after 120 minutes of incubation
C_0 – absorbance for the control sample measured immediately.

Application of extracts into CPSO
Coriander extracts prepared with 70% ethanol were selected for further analyses. CPSO samples were prepared with selected coriander extracts at different concentrations (250, 500 and 1000 ppm). Control samples included: a sample with an addition of the synthetic antioxidant butylated hydroxytoluene ($CPSO_{BHT}$) at 200 ppm and a sample without additives ($CPSO_0$).

Oxidative stability tests of CPSO samples

Schaal oven test. Samples of CPSO with added coriander extracts were exposed to accelerated storage conditions. The samples (50 ± 2 g) were stored in open glass vessels in a dark oven at 63 ± 2 °C with free circulation of heated air. To assess the degree of oxidation, the samples were analyzed for peroxide value (PV) at the beginning and after 4, 8 and 12 days of storage and expressed in $mmolO_2/kg$ and for *p*-anisidine value (AV) in accordance with official standards SRPS EN ISO 3960:2017 and SRPS EN ISO 6885:2017 (Institute for Standardization of Serbia, 2017). The specific absorbance coefficients at the absorption wavelengths of 232 nm (conjugated dienes, CD) and 270 nm (conjugated trienes, CT) were determined following the SRPS EN ISO 3656:2013 standard (Institute for Standardization of Serbia, 2013). All spectrophotometric measurements were performed using Shimadzu UV/VIS-1650PC.
Rancimat test. The oxidative stability of the oil, expressed as the induction period (IP) in hours (h), was determined using the Rancimat apparatus (model 743, Methrom, Herisau, Switzerland) following the Rancimat method, standardised as AOCS Method Cd-12b:1992 (AOCS, 1992). For the analysis, 2.5 g of the oil sample was weighed into a test cuvette. The air flow of 20 l/h was applied while the samples were heated at 100 °C.

Statistical analysis. Data were analyzed using XLSTAT (version 2014.5.03, Addinsoft, New York, USA), analysis and statistics add-in for MS Excel. The results are presented as means ± standard deviation (SD). Statistical significance between means was determined by one-way and two- way ANOVA, followed by post-hoc Tukey's HSD test ($p < 0.05$).

RESULTS AND DISCUSSION

The *β*-CB method is based on discolouration of *β*-carotene due to its reaction with radicals produced by the oxidation of linoleic acid in an emulsion. The rate of *β*-CB can be reduced in the presence of antioxidants (Msaada et al., 2017). Evaluation of antioxidant activity in the *β*-carotene-linoleic acid system showed values ranging from 42.58 to 50.97%. Among the tested extracts, $UAM_{96\%}$ had the weakest antioxidant activity, whereas $SE_{70\%}$ extract demonstrated the strongest antioxidant activity (Table 2). Regardless of the extraction technique used, 70% ethanolic extracts showed stronger activity than 96% extracts. Moreover, all prepared extracts showed weaker activity than the tested synthetic antioxidants, which is consistent with previous literature findings for ethanolic leaf extracts (Yildiz, 2016) and methanolic seed extracts (Msaada et al., 2017).

Table 2. Antioxidant activity of prepared coriander extracts

Type of extract / synthetic antioxidant	*β*-CB (%)
$SE_{70\%}$	51.0 ± 1.8^{bc}
$SE_{96\%}$	45.3 ± 1.8^{de}
$UAM_{70\%}$	49.6 ± 2.7^{cd}
$UAM_{96\%}$	42.6 ± 2.1^{e}
BHT	56.3 ± 1.44^{ab}
BHA	57.7 ± 1.9^{a}

Legend: $SE_{70\%}$ – extract obtained using SE and 70% ethanol; $SE_{96\%}$ – extract obtained using SE and 96% ethanol; $UAM_{70\%}$ – extract obtained using UAM and 70% ethanol; $UAM_{96\%}$ – extract obtained using UAM and 96% ethanol. The values are represented as mean ± SD. Data were subjected to one-way ANOVA (factor: Sample (S) – six levels: SE70%, SE96%, UAM70%, UAM96%, BHT and BHA). Different superscripts within the same column indicate a significant difference of means, according to Tukey's HSD test ($p < 0.05$).

Evaluation of oxidative stability by Schaal oven test.
The Schaal oven test is used for assessing oxidative stability of oils during storage and predicting their stability under heat treatments (Mazaheri et al., 2019). During primary oxidation processes in oils, hydroperoxides are predominantly formed, while secondary oxidation leads to decomposing of peroxides into aldehydes and ketones (Rabiej-Kozioł et al., 2023). The results of oxidative stability assessments using the Schaal oven test are presented in Table 3.

Peroxide value – PV. The peroxide value serves as a quality indicator of the content of primary oxidation products. PV value was initially 0.81 mmolO_2/kg, reaching 156.24 and 201.90 mmolO_2/kg after 12 days for $CPSO_{BHT}$ and $CPSO_0$, respectively. $CPSO_0$ sample was the most susceptible to oxidation under the tested conditions. The PV of $CPSO_{BHT}$ sample remained within the legal limits (6.41 mmolO_2/kg) after 4 days, but increased to 156.24 mmolO_2/kg after 12 days (approximately 193-fold increase compared to the initial value). For oil samples with added coriander extract, the PV ranged from 8.02 to 12.78 mmolO_2/kg after 4 days, from 24.71 to 32.68 mmolO_2/kg after 8 days and from 167.68 to 186.05 mmolO_2/kg at the end of storage. The inhibitory effect of ethanolic coriander extract was previously examined by Farah et al. (2015), demonstrating significant reductions in peroxide and *p*- anisidine values compared to the control oil sample. In this study, the hydroperoxide content in the sample with coriander extract after heating at 60 °C for 28 days was not significantly different from that of the sample with BHT (9.46 meq/kg vs. 9.20 meq/kg, respectively). Under the same conditions, the oxidative changes in the control sample (CPSO without additions) were more pronounced (19.80 meq/kg). The results obtained for the formation of primary oxidation products are closely related to the fatty acid composition. As reported in a previous study, the fatty acid composition of the tested CPSO consists mainly of linoleic acid (75.8%), which is very susceptible to oxidative changes (Stojićević et al., 2023).

***p*-anisidine value – AV**. AV expresses the content of secondary oxidation products formed from unstable hydroperoxides. The initial AV in $CPSO_0$ (0.23) indicates that the oil was obtained from high-quality sunflower seeds, as no oxidative processes had yet taken place and no secondary oxidation products were present. During the test period, an upward trend in AV was recorded for all samples, although the rate of increase varied. A slow increase in AV was observed in the first test period, while a faster increase occurred in all samples between days 8 and 12 of accelerated storage. This trend was expected, as secondary oxidation products are formed at a later stage, and they are closely associated with extensive degradation of unsaturated fatty acids (Sghaier et al., 2017; Lužaić et al., 2022). For oil samples with coriander extract, AV ranged from 0.25 to 0.84 after 4 days, 1.59 to 2.22 after 8 days and 10.29 to 12.69 after 12 days. The increase in AV after 12 days was approximately 55-fold in samples with SE_{250}, SE_{500} and UAM_{250} extracts (12.66, 12.36 and 12.69, respectively) and in $CPSO_0$ (12.40). Under similar experimental conditions, Farah et al. (2015) found lower AV for oil samples with coriander extracts compared to oil samples without additives. Among the tested samples, $CPSO_{BHT}$ had the highest inhibitory effect on the formation of secondary oxidation products, confirming the results of the antioxidant test which indicated that coriander extracts acted as a weaker antioxidant than BHT.

Conjugated dienes – CD. The hydroperoxides of polyunsaturated fatty acids (linoleic and linolenic acid) have strong absorbance at 232 nm (Marmesat et al., 2009). Therefore, measuring the absorbance at this wavelength can provide additional information about the content of primary oxidation products in oil samples. After 4 days of accelerated storage, CD content in the oil samples with coriander extract ranged from 2.75 to 3.32. On 8th day of the test, CD content increased by 3 to 5 times (10.79 - 12.74), and further doubled by the end of the test (26.42 - 29.22). CD content increased from initial 2.31 to 20.44 and 53.12 for $CPSO_{BHT}$ and $CPSO_0$, respectively. Although coriander extracts did not produce the same effect as BHT, its addition was clearly effective in inhibiting the formation of primary oxidation products. Variations in oxidation product accumulation in all samples can be attributed to the type of oil sample used, i.e. to fatty acid composition. As already mentioned, linoleic acid was the predominant fatty acid (75.8) in the analysed oil, followed by oleic acid (16.4%). Previous studies on oxidative stability of sunflower oil with varying fatty acid composition showed that susceptibility of the oil to oxidative changes is closely related to the content of polyunsaturated fatty acids (Marmesat et al., 2009; Romanić and Kravić, 2017; Tinello et al., 2018; Lužaić et al., 2022). The hydroperoxides of linoleic acid contribute to an increase in CD content, while a rise in hydroperoxides of oleic acid increase PV, but without affecting UV absorption at 232 nm (Marmesat et al., 2009). Therefore, hydroperoxides (PV) do not consistently reflect the oxidative status of the sample, especially in the case of heated samples (Sghaier et al., 2017).

Table 3. Results of oxidative stability assessments using the Schaal oven test

Type of extract/ sample	**SE_{70}**			**UAM_{70}**			**$CPSO_{BHT}$**	**$CPSO_0$**
Concentration of extract/ BHT (ppm)	**250**	**500**	**1000**	**250**	**500**	**1000**	**200**	**0**
Storage time (days)	**PV ($mmolO_2/kg$)**							
0	-	-	-	-	-	-	-	0.81 ± 0.05
4	12.06 ± 0.02 ^{A,c}	8.02 ± 0.02 ^{D,c}	8.94 ± 0.01 ^{C,c}	12.78 ± 0.01 ^{A,c}	10.46 ± 0.03 ^{B,c}	10.06 ± 0.02 ^{B,c}	6.41 ± 0.01 ^{E,c}	10.11 ± 0.02 ^{B,c}
8	32.68 ± 0.01 ^{B,b}	27.01 ± 0.01 ^{E,b}	24.71 ± 0.05 ^{F,b}	31.25 ± 0.02 ^{C,d}	28.35 ± 0.01 ^{D,b}	26.37 ± 0.01 ^{E,b}	19.22 ± 0.01 ^{G,b}	63.38 ± 0.07 ^{A,b}
12	182.88 ± 0.04 ^{C,a}	169.98 ± 0.21 ^{E,a}	167.68 ± 0.13 ^{F,a}	186.05 ± 0.37 ^{CD,c}	178.60 ± 0.55 ^{C,c}	169.83 ± 0.54 ^{E,a}	156.24 ± 0.17 ^{G,a}	201.90 ± 0.16 ^{A,a}
AV								
0	-	-	-	-	-	-	-	0.23 ± 0.01
4	0.84 ± 0.01 ^{A,c}	0.61 ± 0.01 ^{B,c}	0.41 ± 0.04 ^{C,c}	0.39 ± 0.01 ^{CD,c}	0.41 ± 0.01 ^{C,c}	0.25 ± 0.01 ^{E,c}	0.40 ± 0.00 ^{C,c}	0.37 ± 0.01 ^{D,c}
8	2.22 ± 0.01 ^{B,b}	1.75 ± 0.01 ^{D,b}	1.59 ± 0.01 ^{F,b}	2.20 ± 0.00 ^{B,b}	1.87 ± 0.01 ^{C,b}	1.71 ± 0.01 ^{E,b}	1.33 ± 0.03 ^{G,b}	3.89 ± 0.09 ^{A,b}
12	12.66 ± 0.00 ^{A,a}	12.36 ± 0.00 ^{C,a}	10.29 ± 0.01 ^{F,a}	12.69 ± 0.01 ^{A,a}	11.14 ± 0.01 ^{E,a}	11.78 ± 0.01 ^{D,a}	8.85 ± 0.02 ^{G,a}	12.40 ± 0.07 ^{B,a}
CD								
0	-	-	-	-	-	-	-	2.31 ± 0.02
4	3.10 ± 0.01 ^{A,c}	3.32 ± 0.01 ^{A,c}	3.31 ± 0.03 ^{A,c}	2.75 ± 0.00 ^{Ab,c}	3.16 ± 0.00 ^{A,c}	3.26 ± 0.01 ^{A,c}	2.51 ± 0.01 ^{B,c}	2.98 ± 0.01 ^{AB,c}
8	12.27 ± 0.03 ^{BC,b}	12.74 ± 0.04 ^{B,b}	11.00 ± 0.00 ^{D,b}	10.79 ± 0.68 ^{D,b}	11.91 ± 0.04 ^{C,b}	11.96 ± 0.01 ^{C,b}	9.89 ± 0.01 ^{E,b}	13.86 ± 0.00 ^{A,b}
12	28.67 ± 0.01 ^{B,a}	28.01 ± 0.01 ^{C,a}	26.87 ± 0.01 ^{D,a}	29.22 ± 0.02 ^{B,a}	27.56 ± 0.03 ^{C,a}	26.42 ± 0.01 ^{D,a}	20.44 ± 0.00 ^{E,a}	53.12 ± 0.00 ^{A,a}
CT								
0	-	-	-	-	-	-	-	0.15 ± 0.01
4	0.22 ± 0.01 ^{C,c}	0.21 ± 0.01 ^{C,c}	0.19 ± 0.00 ^{C,c}	0.25 ± 0.01 ^{B,c}	0.19 ± 0.00 ^{C,c}	0.19 ± 0.00 ^{C,c}	0.15 ± 0.01 ^{D,c}	0.30 ± 0.00 ^{A,c}
8	0.99 ± 0.01 ^{B,b}	0.78 ± 0.01 ^{D,b}	0.75 ± 0.01 ^{E,b}	0.85 ± 0.01 ^{C,b}	0.71 ± 0.01 ^{F,b}	0.52 ± 0.01 ^{G,b}	0.34 ± 0.00 ^{H,b}	1.05 ± 0.00 ^{A,b}
12	1.29 ± 0.01 ^{B,a}	1.23 ± 0.00 ^{C,a}	1.18 ± 0.01 ^{D,a}	1.31 ± 0.01 ^{B,a}	1.26 ± 0.01 ^{C,a}	1.10 ± 0.01 ^{E,a}	0.95 ± 0.01 ^{F,a}	2.81 ± 0.01 ^{A,a}

Legend: The values are represented as mean ± SD. Data were subjected to two-way ANOVA (between-subjects factor: Sample (S) – eight levels: SE_{250}, SE_{500}, SE_{1000}, UAM_{250}, UAM_{500}, UAM_{1000}, $CPSO_{BHT}$ and $CPSO_0$; within-subject factor: Time (T) – three levels: 4, 8 and 12 months. Both factors (S and T) and their interaction (SxT) had a significant effect on all examined parameters ($p < 0.0001$).). Different uppercase superscripts within the same column, and different lowercase superscripts within the same row and same parameter indicate a significant difference of means, according to Tukey's HSD test ($p < 0.05$).

Conjugated trines – CT. The formation of CT, as secondary oxidation products, was less intense compared to CD. This was expected, given that CT are formed as oxidation products of fatty acids, which are hardly present in sunflower oil (Lužaić et al., 2022). The highest increase in CT was found in $CPSO_0$, with 19-fold rise from 0.15 to 2.81 after 12 days of accelerated storage. In comparison, the increase in the samples with coriander extracts was only half as high, ranging between 1.10 and 1.31. The formation of CT was least pronounced in $CPSO_{BHT}$ sample (with values of 0.16, 0.34 and 0.95 after 4, 8 and 12 days of storage, respectively) and was comparable to the potency of the oil sample containing the highest concentration of the extract.

Evaluation of oxidative stability by Rancimat test.

In the Rancimat method, where oxidation is accelerated by increased temperature and air flow, the IP values were evaluated as the time required for achieving an increase in water conductivity, resulting from the production of oxidation-induced fractions (Tinello et al., 2018). The results of this analysis for the tested oil samples are presented in Table 4.

Table 4. Oxidative stability of oil samples evaluated by Rancimat method, expressed as induction period.

Sample	Induction period *(h)*
SE_{250}	7.81 ± 0.02^{b}
SE_{500}	7.79 ± 0.02^{b}
SE_{1000}	7.32 ± 0.18^{d}
UAM_{250}	7.69 ± 0.13^{bc}
UAM_{500}	7.64 ± 0.07^{bc}
UAM_{1000}	7.29 ± 0.12^{d}
$CPSO_{BHT}$	9.26 ± 0.16^{a}
$CPSO_0$	7.42 ± 0.05^{cd}

Legend: SE_{250} – CPSO sample prepared with 250 ppm of SE coriander extract; SE_{500} – CPSO sample prepared with 500 ppm of SE coriander extract; SE_{1000} – CPSO sample prepared with 1000 ppm of SE coriander extract; UAM_{250} – CPSO sample prepared with 250 ppm of UAM coriander extract; UAM_{500} – CPSO sample prepared with 500 ppm of UAM coriander extract; UAM_{1000} – CPSO sample prepared with 1000 ppm of UAM coriander extract; $CPSO_{BHT}$ – CPSO sample prepared with an addition of BHT; $CPSO_0$ sample without additives. The values are expressed as mean ± SD. Data were subjected to one-way ANOVA (factor: Sample (S) – eight levels: SE_{250}, SE_{500}, SE_{1000}, UAM_{250}, UAM_{500}, UAM_{1000}, $CPSO_{BHT}$ and $CPSO_0$). Different superscripts within the same column indicate a significant difference of means, according to Tukey's HSD test ($p < 0.05$).

Under the applied Rancimat test conditions, the IP value for the control sample $CPSO_0$ was 7.42, while the IP value for the oil samples with coriander extracts ranged from 7.29 to 7.81, indicating low efficiency in delaying the formation of oxidation products. $CPSO_{BHT}$ sample had the highest IP value (9.26). At lower concentrations, the addition of coriander extract allowed a slight increase in IP values. However, the addition of 1000 ppm of both coriander extracts showed a slight pro-oxidant effect (7.32 and 7.29 for oil samples with SE and UAM extract, respectively). It should be emphasized that a stronger antioxidant effect was observed for the SE extract. The ANOVA analysis revealed statistically significant difference between all tested samples and the control sample at $p < 0.05$. These findings are consistent with those of Cordeiro et al. (2013), who confirmed that the ethanolic coriander extract acts as a weak pro-oxidant in soybean oil. The pro-oxidant activity was also observed by Aćimović et al. (2017), who measured the extent of lipid oxidation using the thiobarbituric acid assay (TBARS) and found that coriander essential oil (400 ppm) acted as a pro-oxidant in cold-pressed pumpkin seed oil stored at 70 °C. In contrast, Wang et al. (2018) reported that coriander essential oil (1200 ppm) was able to inhibit the oxidative rancidity in refined sunflower oil during accelerated storage.

CONCLUSION

Regardless of the extraction technique, the evaluation of antioxidant activity showed that the samples obtained with 70% ethanol were more effective as antioxidants compared to the samples obtained with 96% ethanol. The tested extracts showed slightly lower antioxidant capacity compared to the tested synthetic antioxidants BHA and BHT.

This finding was also confirmed in oxidative stability tests. The results of the Schaal-oven test indicated that the formation of both primary and secondary oxidation products increased in the later stages of accelerated storage. Although neither of the coriander extracts (SE_{70} and UAM_{70}) was as effective as BHT at all applied concentrations, they both showed certain antioxidant activity and an ability to delay oxidative changes in CPSO. On the other hand, the results of the Rancimat test indicated weak antioxidant activity at lower extract concentrations (250 and 500 ppm) and a slight pro-oxidative effect observed at the highest concentration (1000 ppm). According to the obtained findings, coriander extracts at lower concentrations can serve as natural antioxidants in the food industry, especially for stabilizing CPOs. Further studies could explore other solvents or extraction techniques to produce extracts with effects similar or better than synthetic antioxidants.

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Authors' ORCID iDs: Aleksandra Stojićević (https://orcid.org/0000-0002-0966-6285); Ana Alimpić Aradski (https://orcid.org/0000-0002-0879-6467); Mališa Antić (https://orcid.org/0000-0003-1366-4466); Darko Micić (https://orcid.org/0000-0001-6905-8954).

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