



Food Science and Applied Biotechnology

e-ISSN: 2603-3380

Journal home page: www.ijfsab.com
<https://doi.org/10.30721/fsab2025.v8.i1>



Research Article

From extraction to the synergistic effects of spent red and white grape pomaces on the oil's oxidative stability

Milad Daneshniya¹, Peyman Ebrahimi¹, Dasha Mihaylova², Mohammad Khairul Alam¹, Anna Lante^{1✉}

¹Department of Agronomy, Food, Natural Resources, Animals, and Environment—DAFNAE, University of Padova, Viale dell'Università, 16, 35020 Legnaro, Italy.

²Department of Microbiology and Biotechnology, University of Food Technologies, 26 Maritza Blvd., 4002 Plovdiv, Bulgaria.

Abstract

This study investigates the potential of post-distillation grape pomaces, as a natural source of antioxidants, to inhibit lipid oxidation in vegetable oils. Extracts from both white and red spent grape pomaces (WGP and RGP, respectively) were obtained using conventional extraction, ultrasound-assisted extraction (UAE), and a combination of both methods. The most efficient extraction process was determined based on the total phenolic content and ferric-reducing antioxidant power (FRAP) of each extract. UAE emerged as the optimal method, owing to its lower energy consumption and the higher FRAP values (*i.e.*, 88.61 ± 12.00 mg Trolox equivalent (TE).g⁻¹ dry weight (DW) for WGP and 45.75 ± 4.94 mg TE.g⁻¹ DW for RGP) of the extracts obtained. Incorporating individual and mixed extracts at 30% v/v into various oils resulted in enhanced oxidative stability, as demonstrated by the Rancimat test. The natural extracts performed similarly to butylated hydroxytoluene, a synthetic antioxidant. The mixed extracts exhibited a synergistic effect, further increasing the induction period of oil oxidation, likely due to the mixed phenolic profile of the extracts and the regeneration of one antioxidant by another after neutralizing free radicals. These findings underscore the significant antioxidant potential of spent grape pomace phenolic extracts as natural additives for oil-based food systems, providing reliable data for further research and application in the food industry.

Keywords

lipid oxidation, extraction process, phenolic extracts, by-product valorisation, winemaking by-products

Abbreviations

AAI – Antioxidant Activity Index; IP – Induction Period; BHT – Butylated Hydroxytoluene; BHA – Butylated Hydroxyanisole; DW – Dry Weight; FRAP – Ferric Reducing Antioxidant Power; TPC – Total Phenolic Content; GAE – Gallic Acid Equivalents; RGP – Spent Red Grape Pomace; WGP – Spent White Grape Pomace; TE – Trolox Equivalent; TPTZ – 2,4,6-Tris(2-pyridyl)-s-triazine; UAE – Ultrasound-Assisted Extraction; CE – Conventional Extraction. GPE – Grape Pomace Extract; GPP – Grape Pomace Powder.

✉Corresponding author: Anna Lante, Department of Agronomy, Food, Natural Resources, Animals, and Environment—DAFNAE, University of Padova, Legnaro, Italy. E-mail: anna.lante@unipd.it

Article history:

Received 7 December 2024

Reviewed 17 February 2025

Accepted 5 March 2025

Available on-line 18 March 2025

<https://doi.org/10.30721/fsab2025.v8.i1.492>
2025, UFT Academic publishing house, Plovdiv

Introduction

Lipid oxidation negatively impacts the quality and shelf life of fat-containing foods by generating toxic by-products, deteriorating sensory qualities, and depleting essential nutrients like polyunsaturated fatty acids and vitamins (Bayram and Decker 2024; Cantele et al. 2023; Villeneuve et al. 2023). This presents a significant challenge in maintaining food quality, making oxidation control a priority within food preservation strategies. One possibility to combat this issue is employing synthetic or natural antioxidants in food products. Despite the effectiveness of synthetic antioxidants, such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), their health concerns to consumers have surged the demand for natural alternatives. Natural phenolic extracts could be promising alternatives to synthetic antioxidants and may even reduce risks associated with chronic diseases due to their health benefits (Cantele et al. 2020; Ebrahimi et al. 2025). Therefore, finding a suitable source to obtain phenolic extracts is essential for developing effective, natural antioxidant solutions in food preservation without associated health concerns.

Not only grape pomace, a by-product of wine production composed of grape skins, seeds, and stems, but also spent grape pomaces after distillation are a notable natural antioxidant source rich in polyphenols, tannins, and anthocyanins, with a strong potential for use in food preservation (De Iseppi et al. 2020; Cisneros-Yupanqui et al. 2023; Boruah and Ray 2024). In particular, the phenolic-rich extracts from spent grape pomace have demonstrated considerable potential in delaying lipid oxidation in food systems (Cisneros-Yupanqui et al. 2024). Grape pomace may also offer various health benefits to consumers, including gut health improvement, anticancer potential, and cardioprotective effects (Sinrod et al. 2023). Additionally, employing a by-product can contribute to a circular bioeconomy loop by reducing waste, providing an eco-friendly source of natural preservatives and functional ingredients (Ebrahimi, Khamirakar et al. 2024). To improve the sustainability of the valorisation process of spent grape pomace, the recovery of bioactive compounds can be done using modern extraction methods, such as microwave, ultrasound, and enzymatic treatments, which do not present the drawbacks of

conventional extraction methods, like high temperatures, harsh chemical usage, and high time consumption (Sirohi et al. 2020; Perra et al. 2022). However, identifying an optimal extraction process for recovering bioactive compounds from by-products remains an ongoing challenge (Ebrahimi and Lante 2022). Therefore, it is essential to explore sustainable extraction approaches to achieve the best outcomes in by-product valorisation process (Nutrizio et al. 2024).

In light of these benefits, the current study seeks a biorefinery approach to recover phenolic compounds from red and white spent grape pomace, alone and mixed. In the initial phase of the present study, the focus was on comparing the total phenolic content (TPC) and ferric reducing antioxidant power (FRAP) of spent grape pomace extracts (GPE) obtained through three distinct extraction methods including, conventional extraction (CE), ultrasound-assisted extraction (UAE), and a combined approach incorporating both (CU). This comparative analysis provided a foundation for selecting the optimal extraction method, aiming to maximize the yield of phenolic compounds while enhancing antioxidant efficacy. Following the identification of the optimal extraction method, the next objective was to determine the ideal concentration of the extracts obtained from white/red spent grape pomace and their combined extract to be applied to different edible oils, while comparing to BHT as a reference synthetic antioxidant.

Materials and Methods

Materials. White and red spent grape pomace, derived primarily from Chardonnay and Valpolicella cultivars (*Vitis vinifera*) post-Grappa production, were procured from an industrial distillery located in Padova, Italy. All the vegetable oils were bought from local markets in Padova, Italy. Ethanol (EtOH), Folin-Ciocalteu reagent, gallic acid, sodium carbonate, sodium hydroxide, hydrochloric acid, acetic acid, iron chloride, 2,4,6-Tris(2-pyridyl)-s-triazine (TPTZ), and Tetramethylchromane-2-Carboxylic Acid (Trolox) were obtained from Sigma-Aldrich (St. Louis, MO, USA). All solvents and other chemicals were of analytical grade.

Spent grape pomace powder preparation. Both red and white grape pomaces obtained after distillation underwent a drying process in an oven maintained at 50°C for a duration of 48 h. Subsequently, the dried materials were ground using a water-cooled laboratory mill (IKA Werke M20, Germany) to achieve a particle size smaller than 500 µm. The resulting powders were stored in dark conditions at -18°C until further analysis. Moisture content was assessed in all samples, and all analytical determinations were expressed based on dry weight (DW).

Extraction procedure. The extraction process involved the comparison of three distinct techniques (Fig. 1) according to [Cisneros-Yupanqui et al. \(2024\)](#). For conventional extraction (CE), 1g of powdered red/white spent grape pomace was dissolved in 10 mL of 50% EtOH, and the mixture was incubated at 50°C for 45 min in an agitating water bath. For Ultrasound-Assisted Extraction (UAE), a SONOPULS ultrasonic homogenizer (HD 2200.2, Bandelin, Berlin, Germany) operating at 20 kHz ± 500Hz Frequency and power of 200 W, equipped with a KE76 titanium tip was utilized. The tip was immersed 0.5 cm in a mixture of 1 g powdered red/white spent grape pomace and 10 mL of 50% EtOH. The mixture was sonicated with an amplitude of 25% for 30 min, with a pulsation set at 60 sec operations and 10 s pauses in the middle. An

ice bucket was used to cover the extracting cell to avoid overheating in the system. The third method consisted of a combination of both techniques (CU), wherein the samples underwent treatment for 15 min in the water bath and then sonicated for 15 min with an amplitude of 25%. After the extraction step in all the methods, solid residues were eliminated through centrifugation (10000 ×g for 5 min at 4°C) and filtration with Whatman® paper N°1. The extracts were stored at 80°C until further analysis. The individual extracts and their mixture in three different proportions (Fig.1) were evaluated. The energy consumption in each method was calculated using equation 1.

$$\text{Energy consumption (KJ)} = \frac{\text{Power used (kW)} \times \text{Time (h)} \times 3600}{1} \quad (1),$$

where 3600 is the conversion factor from kWh to KJ.

Total phenolic content (TPC). TPC was determined using Folin-Ciocalteu method according to [Cisneros-Yupanqui et al. \(2024\)](#). In brief, 500 µL of the diluted sample was mixed with 250 µL of 1N Folin-Ciocalteu reagent and 1250 µL of Na₂CO₃ 7.5%. A blank solution, substituting water for the sample, was also prepared. Following a 30-min incubation period in darkness, the absorbance was measured at 755 nm using a UV/Vis

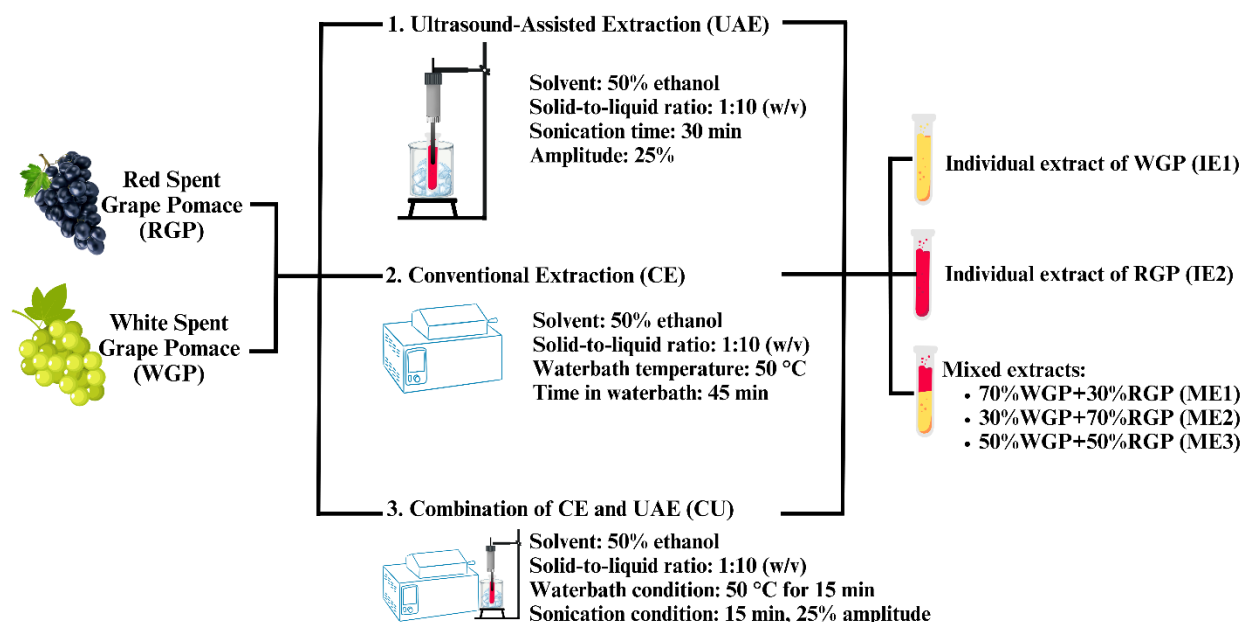


Figure 1. The experimental design of extraction process and the codes of each type of extract

spectrophotometer (Varian Carry 50 Bio UV/Vis, Agilent Technologies, Santa Clara, CA, USA). The results were expressed as mg of gallic acid equivalent (GAE) per g of DW.

Ferric reducing antioxidant power (FRAP). The antioxidant activity of the extracts was conducted utilizing the FRAP method, as described by [Cisneros-Yupanqui et al. \(2024\)](#). The FRAP solution was prepared by combining 2.5 mL of 0.01 M 2,4,6-Tris(2-pyridyl)-s-triazine (TPTZ) in 40 mM HCl, 2.5 mL of an aqueous solution containing 0.02 M FeCl₃, and 25 mL of 0.2 M sodium acetate buffer. Subsequently, 100 µL of the sample was mixed with 900 µL of the FRAP solution and incubated at 37°C for 30 min. Additionally, a blank solution was prepared using the dilution solvent. The absorbance was measured at 593 nm using a UV/Vis spectrophotometer (Varian Carry 50 Bio UV/Vis, Agilent Technologies, Santa Clara, CA, USA). The results were expressed in mg of Trolox equivalent (TE) per g of DW.

Antioxidant activity of the extracts in oil systems. The antioxidant activity of the individual and combined extracts was evaluated in a blend of four edible oils, namely sunflower, soybean, corn, and grape seed oil, as real food systems according to [Ebrahimi et al. \(2025\)](#). For the evaluation, the mixtures of oil and the extracts were first prepared. The mixtures, while covered with ice to avoid overheating, were initially treated with ultrasound with amplitude of 25% for 150 sec, followed by a homogenization process using an UltraTurrax (T-25 model, Janke and Kunkel, Germany) operating at 1000 ×g for 5 min. Butylated hydroxytoluene (BHT) at 0.02% (w/w) was also used as a reference synthetic antioxidant. The official Rancimat method was carried out with 3 g oil-extract mixtures at 110 °C and an airflow of 20 L.h⁻¹. The oxidative stability of the extract-added oils was reported based on the Induction Period (IP), which refers to the time (h) at which the water conductivity (µS/min) starts to increase as a result of the production of volatile compounds involved in the lipid oxidation. The Antioxidant Activity Index (AAI) was calculated using the equation 2.

$$AAI = \frac{IP \text{ of oil with antioxidants}}{IP \text{ of oil without antioxidant}} \quad (2)$$

Statistical analysis. The experimental results are presented as the mean ± standard deviation from

three replications of each experiment. Statistical analysis was conducted using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post hoc test to assess pairwise comparisons, with a significance level of 0.05 considered statistically significant ($p \leq 0.05$). The analysis was performed using SPSS Statistics (Ver. 27.0), and graphical representations of the data were created with Origin Pro 2022 (Northampton, MA, USA).

Results and Discussion

Efficiency of the extraction techniques. Phenolic compounds, known as secondary metabolites in plants, are recognized for their antioxidant properties, holding potential health benefits to consumers including anti-diabetes, anti-obesity, anti-Alzheimer's, etc. ([Ebrahimi and Lante 2021](#)). The choice of the extraction technique in recovery of polyphenols is an essential factor affecting the efficiency of the by-product valorisation process ([Dukić et al. 2022](#); [Vrancheva et al. 2020](#)). This choice can affect the type and concentration of the recovered polyphenols, the antioxidant activity of the extract, and the economic viability of the process ([Ebrahimi, Khamirakar et al. 2024](#)). Additionally, finding the optimal combination of antioxidants is essential for effectively inhibiting lipid oxidation, as certain antioxidants exhibit synergistic effects by regenerating one another, while others may have antagonistic effects ([Bayram and Decker 2024](#); [Bayram and Decker 2023](#)). This section is dedicated to study the efficiency of different extraction techniques, compare the phenolic compounds in red spent grape pomace (RGP) and white spent grape pomaces (WGP), and explore the impact of combining their extracts on the antioxidant activity.

Table 1 presents the effect of the extraction methods on the TPC of individual and combined extracts. The data reveals significant differences in the effectiveness of these methods and the impact of sample mixtures on the TPC values. Among all the extraction techniques, the extracts obtained from WGP had higher TPC values than RGP. This suggests that RGP has less phenolic content than WGP or its phenolic compounds are either less accessible or more prone to degradation under heat.

Table 2 presents the effect of the extraction methods on the FRAP of individual and combined extracts. The FRAP assay measures the ability of a compound to reduce Fe^{3+} to Fe^{2+} in the presence of a reducing agent. This reduction leads to a change in absorbance at 593 nm, which is directly proportional to the antioxidant capacity of the compound being tested (Gonzalez et al. 2018). Transition metals (Fe^{2+} , Fe^{3+} , and Cu^{2+}) are among the most prevalent prooxidants in food products due

to their ability to generate alkyl radicals and break down lipid hydroperoxides into peroxy and alkoxy radicals. If an extract can reduce ferric ions to ferrous ions, it may serve to inhibit lipid oxidation in food systems (Ebrahimi et al. 2025). Therefore, the effectiveness of the UAE method in producing phenolic-rich extracts with significantly higher FRAP values highlights its potential for obtaining extracts capable of slowing oxidation in real food systems.

Table 1. The effect of the extraction methods on the TPC (mg GAE.g⁻¹ DW) of individual and combined extracts

Extracts	Extraction method		
	UAE	CE	CU
IE1	38.11±3.18 ^{Db}	7.89±0.55 ^{Ba}	45.59±2.48 ^{Cc}
IE2	16.50±0.17 ^{Ab}	4.76±0.42 ^{Aa}	23.49±3.70 ^{Ac}
ME1	24.23 ±0.23 ^{Bb}	20.17±0.77 ^{Ea}	35.28±1.31 ^{Bc}
ME2	20.48±0.37 ^{Bb}	14.49±0.92 ^{Ca}	30.52±2.35 ^{Bc}
ME3	28.87±2.18 ^{Cb}	16.43±0.42 ^{Da}	33.29±4.64 ^{Bb}

*Results are reported as mean ± standard deviation (n=3). Different capital letters in each column and different small letters in each row indicate significant differences ($p \leq 0.05$), as assessed by one-way ANOVA and Tukey's honestly significant difference tests.

Table 2. The effect of the extraction methods on the FRAP (mg TE.g⁻¹ DW) of individual and combined extracts

Extracts	Extraction methods		
	UAE	CE	CU
IE1	88.61±12.00 ^{Cb}	29.79±1.96 ^{ABa}	71.39±3.95 ^{Bb}
IE2	45.75±4.94 ^{Ab}	24.39±4.98 ^{Aa}	42.99±2.49 ^{Ab}
ME1	67.52±9.97 ^{BCb}	30.13±0.79 ^{ABa}	105.51±10.28 ^{Cc}
ME2	55.04±4.13 ^{ABb}	41.30±1.09 ^{Ca}	63.84±5.82 ^{Bb}
ME3	72.62±6.06 ^{BCc}	33.10±3.38 ^{Ba}	56.37±6.82 ^{ABb}

*Results are reported as mean ± standard deviation (n=3). Different capital letters in each column and different small letters in each row indicate significant differences ($p \leq 0.05$), as assessed by one-way ANOVA and Tukey's honestly significant difference tests.

In all the samples, the extracts obtained via UAE had significantly higher TPC and FRAP values compared to CE method. This is because the UAE method employs high-frequency sound waves to create cavitation bubbles in a liquid medium, which collapse and generate intense local pressure and temperature. This mechanical action disrupts the cell walls of plant materials, facilitating the release of intracellular compounds, including phenolics (Ebrahimi and Lante 2022). The lower TPC and antioxidant activity of the extracts obtained via CE method indicates that it can deteriorate the content and activity of phenolic compounds due to high temperatures. Žlabur et al. (2020) compared CE and

UAE techniques for extraction of polyphenols from Chamomile flowers, and they reported that the UAE method notably reduces extraction time and increases polyphenolic content and antioxidant capacity. These findings highlight the limitations of the CE method in terms of both efficiency and extraction capacity, particularly for samples rich in RGP. However, the heat treatment in CE can also enhance the solubility of some phenolic compounds.

When these two extraction methods were combined together these values increased significantly. The combined method (CU) aims to leverage

the strengths of both approaches: the mechanical disruption of ultrasonic waves and the enhanced solubility provided by heat. This combined method introduced the highest TPC and FRAP values among all methods, indicating a synergistic effect. For the WGP extract, the TPC value was 45.59 ± 2.48 mg GAE.g⁻¹ DW, the highest observed in this study, suggesting that the combined action of ultrasound and heat can maximize the release of phenolic compounds from this type of sample. In the study by Zainal et al. (2022), a combination of maceration and ultrasound-assisted extraction with 70% aqueous ethanol and longer extraction times yielded the highest TPC for *Tetrigona apicalis*, Malaysian propolis.

The energy consumed per extraction round with 1 g of sample in 10 mL of solvent was 22.5 kJ for UAE, 5670 kJ for CE, and 1901.25 kJ for CU. Given that the UAE method showed higher antioxidant activity for most samples and required significantly less energy than the other methods, it was selected as the preferred extraction method for polyphenols to be added to the oil in the next phase of this research. This choice aligns with sustainability goals, as UAE is faster, more energy-efficient, and environmentally friendly compared to traditional methods. Additionally, among the mixed extracts, the 50% RGP + 50% WGP combination (ME3), with a TPC value of 28.87 ± 2.18 GAE.g⁻¹ DW and FRAP value of 72.62 ± 6.06 mg TE.g⁻¹ DW, was chosen due to its balanced composition and high antioxidant activity. This selection not only ensures a rich phenolic content but also leverages the health benefits of both red and white spent grape pomace, supporting the research's objectives of enhancing oil stability and promoting sustainable extraction practices.

The antioxidant activity of the selected extracts in real oil systems. After choosing the UAE as the optimum method for the extraction process, the antioxidant activity of the selected extracts (IE1, IE2, and ME3) in real oil systems was investigated using the Rancimat method. In the Rancimat method, volatile oxidation products formed due to high temperature and airflow create a breakpoint in the conductivity curve. The time at which this breakpoint appears is called the induction period; a shorter induction period indicates quicker lipid oxidation (Ebrahimi et al. 2025). This test is performed at accelerated shelf-life conditions at

110°C with continuous airflow, meaning that even a small increase in the induction period corresponds to a more apparent shelf life at real-life conditions.

A preliminary test was conducted using soybean oil to identify the optimal extract concentration for extending the shelf life of edible oils (Fig. 2). For this purpose, soybean oil fortified with individual RGP extract (IE2 obtained by the UAE method) at concentrations of 5, 10, 20, and 30% v/v, along with a blank oil without extract was studied. The primary objective was to measure the effectiveness of different concentrations in delaying oxidation by considering the IP and AAI for the oil samples. The selection of soybean oil for the preliminary test was due to its high content of unsaturated fatty acids, which makes it highly susceptible to oxidation (Cherif and Slama 2022). Results show that concentrations above 5% provided significant antioxidant activity, with 30% demonstrating the strongest effect ($p \leq 0.05$). This concentration was therefore selected for further testing with different oils in the next phase of the study. Similar to the present study, a dose-dependent increase in the oxidative stability of edible oils after adding GPE was reported by Poiana et al. (2022).

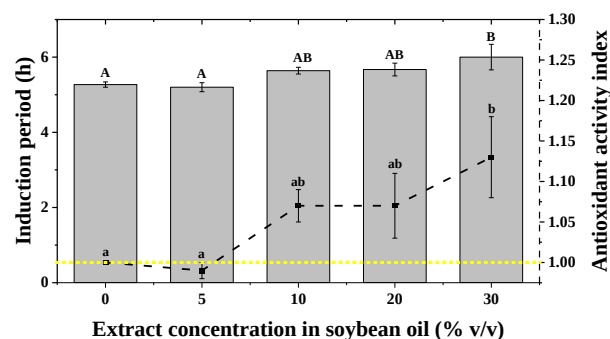


Figure 2. The impact of different concentrations of red spent grape pomace extract on the induction period and antioxidant activity index. Bars show the induction period, the thick (black) dashed line shows the antioxidant activity index, and the thin (yellow) dashed line compares the antioxidant activity index with blank oil.

*Results are presented as mean $\pm$ SD ($n = 3$). Different characters show a significant difference ($p \leq 0.05$) among the samples, as assessed by one-way ANOVA and Tukey's honestly significant difference tests.

Based on the preliminary test results (Fig. 2), different vegetable oils were fortified with 30% v/v

of individual or combined extracts of RGP and WGP. As a reference synthetic antioxidant, BHT at 0.02% was also tested in the oils. The formation of volatile secondary oxidation products was then measured before and after adding these extracts (Table 3). Results show that IP and AAI in all types of oils increased significantly ($p \leq 0.05$) after the addition of the antioxidants. A similar increase in the oxidative stability of the edible oil using phenolic extracts from grape pomace was reported in the literature (Cisneros-Yupanqui et al. 2022; Poiana et al. 2022; Zhu et al. 2018; Cisneros-Yupanqui et al. 2024). This increase could be associated with the capacity of phenolic compounds to donate hydrogen to free lipid radicals and their transition metal (Fe^{2+} , Fe^{3+} , and Cu^{2+}) chelation activity (Ebrahimi et al. 2025; Ebrahimi, Bayram, Lante et al. 2024).

Moreover, results showed that spent GPE, mainly the mixed variety, significantly enhance the oxidative stability of various edible oils. This is an indicator of the synergistic effect of the pomaces on each other when mixed in equal ratios, as the mixture performed better than pure extract in oxidation inhibition. Antioxidants can regenerate each other when present together, a process where one antioxidant reactivates another after it has neutralized free radicals. This regeneration effect

amplifies the antioxidative impact, allowing antioxidants to work in cycles and providing prolonged protection. Previous studies also support this synergistic interaction, showing that combinations of antioxidants can perform more effectively than individual types alone (Reddy et al. 2020; Brglez Mojzer et al. 2016; Bayram and Decker 2023; Bayram and Decker 2024).

According to the data (Table 3), spent GPEs offered superior protection compared to synthetic antioxidants like BHT at 0.02%, which is the maximum permissible level of BHT as established by Codex Alimentarius (Codex Alimentarius 2023). Similarly, Poiana et al. (2022) reported that high concentrations of GPE had a better antioxidant effect on sunflower oil. Zhu et al. (2018) also confirmed the similar results. These findings underscore the potential for using natural spent GPEs as effective antioxidants to improve the shelf life and quality of edible oils, providing a natural and potentially healthier alternative to synthetic options. The more efficient inhibition of lipid oxidation with the extracts of spent grape pomace could be related to its phenolic profile, which contains catechin, epicatechin, gallic acid, procyanidin B1, and procyanidin B2, making it able to increase the oxidative shelf life of oil-containing foods (Cisneros-Yupanqui et al. 2023).

Table 3. Oxidative stability of different oils fortified with the spent grape pomace extracts and BHT, measured by the Rancimat test

Samples	Soybean Oil		Sunflower Oil		Corn Oil		Grapeseed Oil	
	Induction time, h	AAI	Induction time, h	AAI	Induction time, h	AAI	Induction time, h	AAI
Control Oil	5.27±0.07 ^a	1.00±0.00 ^a	3.92±0.07 ^a	1.00±0.00 ^a	10.55±0.27 ^{ab}	1.00±0.00 ^a	4.31±0.01 ^a	1.00±0.00 ^a
Oil+IE1	6.01±0.22 ^{bc}	1.14±0.05 ^{bc}	4.50±0.10 ^b	1.15±0.03 ^b	11.87±0.12 ^c	1.13±0.02 ^c	5.06±0.10 ^b	1.18±0.02 ^b
Oil+IE2	6.00±0.34 ^{bc}	1.14±0.05 ^{bc}	4.30±0.28 ^{ab}	1.10±0.07 ^{ab}	11.17±0.17 ^b	1.06±0.02 ^b	5.07±0.02 ^b	1.18±0.01 ^b
Oil+ME3	6.29±0.08 ^c	1.19±0.02 ^c	4.43±0.04 ^b	1.13±0.03 ^b	11.92±0.38 ^c	1.13±0.03 ^c	5.49±0.10 ^c	1.27±0.02 ^c
Oil+BHT	5.76±0.39 ^{ab}	1.09±0.00 ^b	4.32±0.19 ^{ab}	1.10±0.07 ^{ab}	10.60±0.14 ^a	0.95±0.04 ^a	4.92±0.16 ^b	1.14±0.04 ^b

*Results are reported as mean ± standard deviation (n=3). Different letters in each column indicates a significant difference ($p \leq 0.05$), as assessed by one-way ANOVA and Tukey's honestly significant difference tests.

The improvement in oxidative stability from spent GPEs opens up possibilities for enhancing the quality of other food products. For example, adding microencapsulated GPE to beef burgers outperformed synthetic antioxidants in reducing lipid and protein oxidation, positioning it as a promising natural antioxidant for the meat industry (dos Santos Silva et al. 2022). However, in certain applications, spent GPEs may increase nutritional

value without extending shelf life. For instance, adding grape pomace to breadsticks raised polyphenol content but accelerated oxidation, reducing shelf life despite nutritional gains (Bianchi et al. 2021). Various factors, including food structure, antioxidant type and concentration, and environmental conditions, affect oxidative stability, highlighting the complex but essential role of antioxidants in food preservation (Culler et al. 2022; Villeneuve et al. 2023; Cantele et al. 2025).

Conclusions

The findings of this study highlight the potential of using natural spent GPE as effective, environmentally friendly alternatives to synthetic antioxidants for improving the shelf life and quality of edible oils. The ability of these natural extracts to outperform traditional synthetic options not only aligns with the growing consumer preference for natural ingredients but also supports sustainable practices by utilizing agricultural by-products. Moreover, the study underscores the importance of selecting appropriate extraction methods and concentrations to maximize the antioxidant properties of spent GPE. These findings contribute to the growing body of evidence supporting the use of natural antioxidants as a sustainable alternative to synthetic options, aligning with the increasing consumer demand for natural and health-promoting food additives. Future research should focus on optimizing extraction parameters, exploring different ratios of the extract on the oils, and exploring the application of spent GPE in other food systems to fully realize their potential benefits.

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