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Natural Antioxidants from Dehydrated Orange (*Citrus sinensis* L.) Peels: A Novel Approach to Mitigate Carcinogenic Substances in Used Cooking Oil

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Abstract

This research examines the effectiveness of dehydrated orange (*Citrus sinensis* L.) peel as a natural antioxidant agent to improve the quality and deterioration of used cooking oil. Orange peel powder was produced from fresh peels obtained from a traditional market in Cairo City, thereafter dried and processed to a consistent particle size. Different amounts of orange peel powder (5, 10, 15, and 20 g/100 mL oil) were incorporated into waste cooking oil, and the chemical and physical properties were assessed. The findings revealed that the control oil had a low content of free fatty acids and peroxides. Still, the used cooking oil (UCO) showed markedly elevated values, indicative of oxidative deterioration. Treatments (T) using dehydrated orange peel had differing impacts on AV and PV, with T1 (5 g/100 mL) displaying the highest values, indicating a pro-oxidant effect at this dose. Nonetheless, elevated amounts (T2, T3, and T4) significantly decreased oxidation indicators, improving the nutritional profile via an increase in advantageous fatty acids such as α-linolenic acid. The photometric colour index (PCI) indicated that reduced amounts markedly darkened the oil, whilst elevated concentrations preserved a hue more like that of the utilised oil. The viscosity measurements indicated that treatments with higher concentrations yielded reduced viscosities, possibly enhancing oil efficacy during frying. According to the findings, dried orange peel may improve the quality and performance of used cooking oil as a natural antioxidant, thus supporting sustainability in the food industry.

Keywords: Natural antioxidants, used cooking oil, desiccated orange peel, oxidative stability, sustainable food processing.

1. Introduction

Deep frying is a widely used and conventional cooking technique used worldwide, distinguished by its specific heat and mass transmission mechanisms. To save expenses, oils are often reused for frying on several occasions. The repeated heating results in observable physical changes in the oil, including heightened viscosity and colour darkening, which may substantially modify its fatty acid content [1]. The heat deterioration of frying oil encompasses intricate chemical events, such as oxidation, hydrolysis, and polymerization [2]. These processes produce different oxidative byproducts, including hydroperoxides and aldehydes, which may be absorbed by fried foods, presenting significant health hazards [3].

Global vegetable oil production was over 210.3 million metric tons in the 2022–2023 marketing year, and projections indicate that this amount will increase to almost 217 million metric tons in 2023–2024. Frying is favoured because it may enhance the flavour and quality of food, but the frequent use of oil introduces harmful substances that may have an adverse effect on human health as well as food quality. Long-term exposure to high temperatures and oxygen speeds up chemical reactions that break down vegetable oil, producing volatile compounds that compromise the oil's integrity [5, 6].

The degree of these chemical reactions is influenced by the frying conditions, including temperature and oil quality. Excess oxygen encourages oil to oxidise at high temperatures, leading to structural changes that deteriorate oil quality and pose health risks [7]. According to studies, heating vegetable oils to about 180 °C may change their molecular makeup and reduce elements that are susceptible to heat, such as vitamin E. Two crucial processes that impact the stability of heated cooking oil are thermal oxidation and auto-oxidation. Cooking oils must have a high degree of oxidative stability from a nutritional standpoint. However, oils that include large levels of trans and saturated fatty acids may be harmful to health.

In developing nations, the consumption of deep-fried dishes is notably elevated, with oils being reused until disposal, leading to what is referred to as waste cooking oil. Repeated heating of oil results in physical abnormalities, such as heightened viscosity and colour darkening, as well as changes in fatty acid makeup [9]. The continuous heating method facilitates a sequence of chemical processes, producing oxidative byproducts that may be absorbed by food. Additionally, heating oil

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continuously speeds up lipid oxidative degradation, which lowers the natural antioxidant levels in the used cooking oil and produces harmful reactive oxygen species. Long-term consumption of food prepared with used oil can seriously impair the body's antioxidant defences, resulting in health issues like diabetes, high blood pressure, and vascular inflammation. Studies have indicated that the use of these oils is linked to decreased levels of high-density lipoproteins (HDLs) and increased levels of triglycerides, malondialdehyde (MDA), low-density lipoproteins (LDLs), and total cholesterol [10].

The reuse of heated vegetable oil for cooking is prevalent in both household and commercial environments, mostly to save food preparation expenses. Since the heating process creates harmful lipid peroxidation byproducts linked to the development of several ailments, such as cancer and cardiovascular disease, this strategy poses significant health risks [11]. The recurrent ingestion of heated oil is linked to heightened risks of cardiovascular diseases due to its impact on serum lipid profiles, blood pressure, and the facilitation of atherosclerosis. Moreover, the use of such oils may result in hypertension, atherosclerosis, osteoporosis, and adverse effects on liver and kidney function. Conversely, research indicates that fresh palm and soybean oils do not have adverse impacts on cardiovascular risk factors or organ health.

Multiple studies have emphasised the possibility for more sustainable use of cooking oil, including adsorption techniques using carbon-based adsorbents derived from coconut shells, wood, and coal, which have been processed to produce activated charcoal. This study's main goal is to determine how well-dehydrated orange (*Citrus sinensis* L.) peel works as a natural antioxidant to improve the stability and quality of used cooking oil. This study aims to determine the best treatment plan that not only enhances oil quality but also supports environmentally friendly food processing methods by examining the effects of different orange peel concentrations on important oxidative indicators, the fatty acid composition, and the physical characteristics of the oil. The study's ultimate goal is to provide important new information on the possibilities of using food waste—like orange peels—as a functional ingredient to enhance the nutritional value and safety of cooking oils.

Materials and Methods

Materials and Chemicals

Used cooking oil (UCO) was purchased from food vendors and eateries in the area. Analytical grade n-hexane for oil extraction purposes. An authentic agent prepared standardized solutions for the measurement of the following values: anisidine value (AnV), iodine number (IV), peroxides content (PV), and free fatty acid content (AV).

Preparation & Treatments of Orange Peel

Powdered orange (*Citrus sinensis* L.) peels were obtained from a conventional market in Cairo. The peels were meticulously cleansed to eliminate any contaminants and then air-dried until all moisture was fully evaporated. After drying, the peels were pulverized into a fine powder and sifted to achieve a particle size of 450 µm for homogeneity. The resultant powder was maintained at ambient temperature until further use.

Batch treatments T1, T2, T3, and T4 involved immersing various weights of orange peel powder (5 g, 10 g, 15 g, and 20 g) in 50 mL of used cooking oil. To compare with different treatments, a control sample was employed. To improve the extraction of the bioactive ingredients from the orange peel into the oil, the solutions were shaken for three hours. After the stirring operation, the mixtures were maintained at ambient temperature for a week to facilitate more interaction between the orange peel powder and the oil. Subsequent to the storage duration, the mixes were filtered to eliminate the solid residues. The lipid profiles of the treated oils were assessed using a spectrophotometric technique at an absorption wavelength of 546 nm. The purpose of this method of preparation and treatment was to assess the potential antioxidant benefits of dried orange peel on the stability and quality of used cooking oil.

Methods

Assessment of Free Fatty Acids

The authorized AOAC (2016) approach was used to determine the acid value (AV) by titrating a measured weight of oil with a standardized KOH solution and utilizing phenolphthalein as an indicator. Using the following formula, the average value was calculated:

$$AV\ (mg/g) = \frac{V\ x\ N\ x\ 56.1}{W}$$

Let W stand for the weight of the oil sample (g), N for the KOH's normality, and V for the amount of KOH utilized (mL).

Peroxidation Level

The AOAC Official Method 965.33 (2016) was used to determine the peroxide value (PV) [12]. A 250–300 mL flask fitted with a ground-glass stopper was filled with around 2 grams of the oil sample. After adding ten millilitres of chloroform, the liquid was stirred for 10 minutes. Then, 2 g of sodium bicarbonate (NaHCO3) and 15 mL of glacial acetic acid were added. One millilitre of saturated potassium iodide (KI) solution was added after stirring, and the amalgamation was stirred for one minute before being left in the dark for five minutes. Then, 0.5 mL of starch solution and 75 mL of distilled water were added. A 0.002 N sodium thiosulfate (Na2S2O3) solution was used to titrate the resulting solution until the blue colour disappeared. The identical procedure, but without the oil sample, was used to create a blank. The following formula was used to calculate the examined oil's peroxide value:

$$PV\ (meq./kg) = \frac{(V1 - V2)\ x\ N\ x\ 1000}{W}$$

Whereas V1 shows the volume of sodium thiosulfate solution used in the sample titration (mL), V2 indicates the volume of sodium thiosulfate used in the blank titration (mL), N indicates that the sodium thiosulfate is normal, and W specifies the weight of the oil sample (g).

Anisidine Value (AnV)

The method described by Harold et al. [13] was used to determine the anisidine value using a Rayleigh UV-2601 UV/VIS spectrophotometer (Hewlett Packard 8452). A 25 mL volumetric flask was promptly filled with a suitable amount of the prepared test sample (about 1

milligram), dissolved in 5 to 10 mL of isooctane, and diluted to the appropriate level using the same solvent (test solution). One millilitre of glacial acetic acid was added to five millilitres of the test solution that had been transferred to a test tube. After that, the tube was sealed and shaken vigorously (unreacted test solution). After two minutes, the solution was moved to a dry, clean spectrometer cell, and the absorbance at 350 nm (A0) was measured. One millilitre of the anisidine reagent was added to a test tube containing five millilitres of the test solution. After that, the tube was sealed and shaken vigorously (reacted test solution). For eight minutes, the test tube was kept at 23 ± 3°C in complete darkness. Within two minutes, the solution was moved to a dry, clean spectrometer cell. The absorbance at 350 nm (A1) was measured after the anisidine reagent was added, after a cumulative reaction time of 10 ± 1 minutes. 5 mL of isooctane and 1 mL of the anisidine reagent were added to a test tube, and the tube was shaken to generate a blank. For eight minutes, the test tube was kept at 23 ± 3°C in complete darkness. Within two minutes, the solution was moved to a dry, clean spectrometer cell. After adding the anisidine reagent, the absorbance was measured at 350 nm (A2) after a total reaction time of 10 ± 1 minutes. The following formula was used to get the anisidine value:

$$p\text{-}AV = 100 * Q * V\,[1.2 * (A_1 - A_2) - A_0) / M$$

Where Q is the sample solution's measured concentration (g/cm³) (Q = 0.01 g/cm³), V is the volume in which the sample was dissolved (cm³) (V = 25 mL), A0 is the unreacted solution's absorbance, A1 is the reacted solution's absorbance, A2 is the blank's absorbance, and M is the test sample's mass (g).

Iodine Value (IV)

To evaluate the level of unsaturation in the oil samples, the iodine value (IV) was calculated. Following conventional procedures, a certain amount of Wijs solution—which contains iodine monochloride—was made. [12] After weighing, around 0.5 g of the oil sample was added to a 250 mL Erlenmeyer flask that had been cleaned and dried. Wijs solution (25 mL) was added to this flask. To avoid iodine photodegradation, the mixture was gently swirled to guarantee complete mixing and then left to react at room temperature for 30 minutes in the dark. After the reaction time, a standardized sodium thiosulfate solution (0.1 N) was used to titrate the excess unreacted iodine until a light yellow colour was seen. A blue complex formed when 1 mL of starch indicator solution was introduced at this stage. Until the blue color vanished, signifying the endpoint, the titration proceeded. It was noted how much sodium thiosulfate (V) was used in the titration. The following formula was used to get the iodine value:

$$IV\ (g/100g) = \frac{V\ (B - S)\ x\ N\ x\ 126.9}{W}$$

N is the sodium thiosulfate's normality, W is the weight of the oil sample (g), V is the amount of sodium thiosulfate utilized (mL), B is the volume of sodium thiosulfate for blank titration (mL), and S is the volume of sodium thiosulfate for sample titration (mL).

Value of Totox

To assess the oxidative breakdown of lipids in the oil samples, the total oxidation value (TOTOX) was computed. The total of the anisidine value (AnV) and peroxide value (PV) is known as the TOTOX value. The computation was done using the following formula:

$$Totox\ value = 2\ PV + p\text{-}AV$$

AnV represents the anisidine value derived from earlier studies, and PV represents the peroxide value. This methodology provides a thorough assessment of oil quality by taking into consideration both primary and secondary oxidation products.

Refractive Index (RI)

A calibrated refractometer (Refractive Index Cell RX4, Mettler ToledoTM, Singapore) was used to test each oil sample's refractive index at a regulated temperature of 20 °C. After the sample had stabilized, a little drop of oil was applied to the refractometer's prism surface, and the reading was obtained. This measurement sheds light on the oil's composition and purity.

Specific Gravity (SG)

The oil samples' specific gravity was measured using a calibrated hydrometer (Baume 64-72, New Jersey, USA). A known volume of oil (typically 50 mL) was poured into a clean graduated cylinder. The hydrometer was gently lowered into the oil until it floated freely without touching the sides of the cylinder. The specific gravity was read directly from the scale on the hydrometer at the liquid's surface level, ensuring that readings were taken at room temperature for accuracy [13].

Composition of Fatty Acids

Gas chromatography (GC) was used to determine each oil sample's fatty acid makeup, per Ibrahim et al. [14]. Oils were transesterified with methanol and sulfuric acid to create fatty acid methyl esters (FAMEs) before examination. In a sealed test tube, around 50 mg of oil, 10 mL of methanol, and 0.5 mL of concentrated sulfuric acid were heated to 70 °C for 60 minutes while being shaken occasionally. Following cooling, n-hexane was used to extract the FAMEs, and GC was used for analysis. An HP 6890 plus gas chromatograph fitted with a flame ionization detector (FID) was used to improve the gas chromatography conditions for separation and quantification. A SupelcoTM SP-2380 capillary column (30 m × 0.25 mm × 0.20 µm) was utilized for the separation process. After three minutes at 50 °C, the starting column temperature was raised to 225 °C at a rate of 10 °C per minute and maintained there for ten more minutes. The split ratio was 1:100 and the injection volume was 1.0 µL. The carrier gas was helium, which flowed at a rate of 1.2 mL/min. Peak regions were used to determine the relative amounts of fatty acids, which were determined by comparing retention durations with established standards.

Photometric Colour Index (PCI)

A UV-Vis spectrophotometer (Hewlett Packard 8452) was used to measure absorbance values at particular wavelengths in order to calculate the photometric colour index (PCI). In order to guarantee that absorbance measurements were within quantifiable bounds, oil samples were suitably diluted with n-hexane. Wavelengths of 460 nm, 550 nm, 620 nm, and 670 nm were used to measure absorbance. The following formula was used to determine the PCI:

$$PCI = (1.29 * Abs._{460}) + (69.7 * Abs._{550}) + (41.2 * Abs._{620}) - (56.4 * Abs._{670})$$

where absorbance levels at particular wavelengths are represented by A.

Viscosity Characteristics

A Brookfield CAP2000 Viscometer (Brookfield Engineering, USA) was used to measure the oil samples' viscosity properties. This laboratory viscometer is designed to provide detailed viscosity flow curves and temperature profiles, making it ideal for research and development applications. The measurements were conducted at various temperatures to evaluate the oils' flow characteristics under conditions that simulate frying operations. The viscometer's precision and ability to handle a wide range of viscosities ensure accurate assessments of the treated oils, facilitating a comprehensive analysis of how dehydrated orange peel influences the viscosity of used cooking oil.

Statistical examination

Version 26.0 of SPSS (Statistical Package for the Social Sciences) was used to do the statistical analysis. For all quantitative analyses, the data were shown as mean ± standard deviation (SD). The significance of group differences was assessed using a one-way analysis of variance (ANOVA), and multiple comparisons were then assessed using Tukey's post-hoc test. Statistical significance was defined as a p-value of less than 0.05.

Results and discussion

This research presents a thorough examination of the chemical and physical properties of used frying oil subjected to different quantities of dried orange peel. The results underscore the influence of orange peel treatments on essential metrics like AV, PV, AnV, and TV, which are vital markers of oil quality and oxidative stability. In order to determine the effectiveness of dried orange peel as a natural antioxidant, the study evaluates the fatty acid content, photometric colour index (PCI), and viscosity properties of the treated oils. Our knowledge of orange peel's efficacy in enhancing the quality and utilization of used cooking oil, as well as its implications for sustainable food processing methods, is improved by comparing our findings with earlier research. The specific findings and their relevance to the fields of food science and oil quality management will be discussed in the sections that follow.

Characterization of treated oil samples in comparison to the control

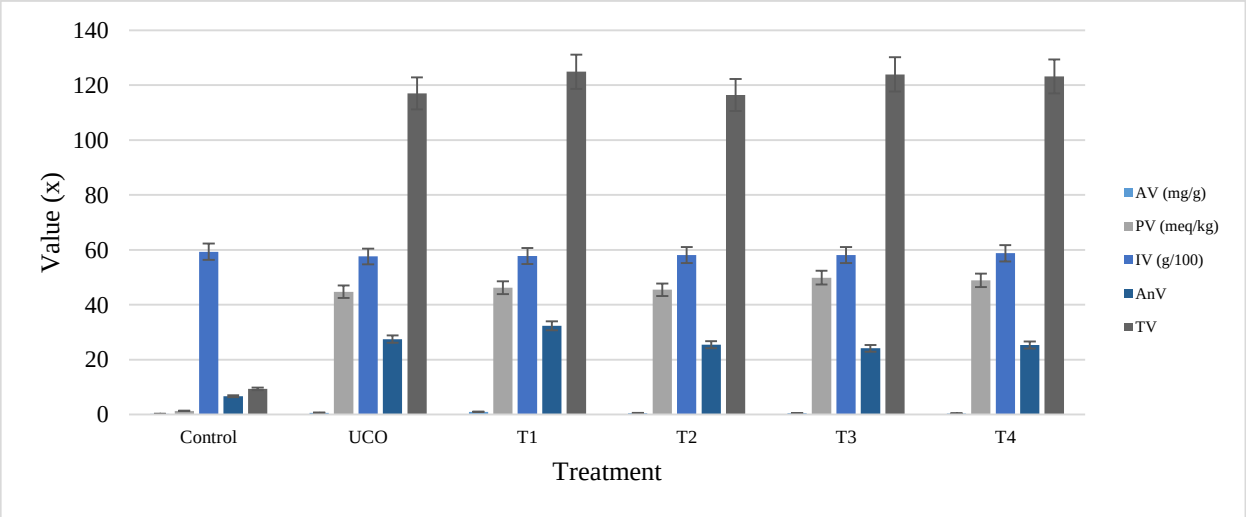
Chemical Properties

Acid Value (AV):

The control oil has a free fatty acid content of 0.25 ± 0.03 mg/g, signifying great quality, but the used cooking oil (UCO) presents a markedly elevated AV of 0.66 ± 0.03 mg/g, indicative of the buildup of free fatty acids resulting from oxidative degradation during frying (Fig 1). The treatments using dehydrated orange peel show differing antioxidant values, with T1 (1.02 ± 0.03 mg/g) presenting the greatest value, indicating a possible pro-oxidant impact at this lower dosage. This corresponds with earlier research suggesting that diminished levels of antioxidants may sometimes intensify oxidation processes, whilst elevated quantities are more efficacious in mitigating AV owing to their superior antioxidant capabilities [3].

Primary oxidation (PV):

The PV is minimal in the control oil (1.37 ± 0.28 meq/kg) and markedly elevated in UCO (44.76 ± 1.04 meq/kg), indicating substantial primary oxidation (Fig 1). The treatments exhibit a complicated pattern, with T1 displaying the greatest PV (46.24 ± 0.04 meq/kg), suggesting that the incorporation of orange peel at this dosage may be inadequate in providing sufficient antioxidant activity to mitigate oxidation. In contrast, the PV values for T2 (45.49 ± 0.68 meq/kg), T3 (49.89 ± 0.61 meq/kg), and T4 (48.91 ± 1.38 meq/kg) indicate a marginal rise in oxidation levels, maybe resulting from the oil's breakdown during treatment. This observation aligns with research indicating elevated PVs in oils subjected to certain natural extracts, particularly at reduced doses [15].



Orange peel concentrations in treated oil samples are indicated by the letters T1, T2, T3, and T4; AV stands for acid value, PV for peroxide value, IV for iodine value, AnV for anisidine value, TV for calculated tox value, and UCO for used cooking oil.

Figure 1. Chemical and physical properties of used frying oil subjected to different quantities of dried orange peel.

Iodine Value (IV)

The IV is consistently steady throughout treatments, with the control measuring 59.31 ± 0.01 g/100 g and UCO at 57.60 ± 0.10 g/100 g (Fig 1). This stability signifies that the oils' unsaturation levels are maintained despite the treatments, essential for oil quality. The uniformity of IV across samples indicates that the incorporation of dried orange peel does not substantially modify the unsaturation level, corroborating evidence demonstrating the durability of iodine levels in oils subjected to natural antioxidants [16].

Secondary and total oxidation (AnV & TV)

The AnV indicates secondary oxidation, with T1 exhibiting the highest value (32.38 ± 0.33), indicating considerable deterioration (Fig 1). The computed Totox value (TV) aligns with this trend, with T1 at 124.88 ± 0.24, indicating that reduced amounts of orange peel may be ineffective in preventing oxidation. Studies indicate that elevated quantities of antioxidants are essential for the efficient reduction of secondary oxidation products [1, 16].

Interpretation of the obtained results

Important information about the efficacy of dried orange peel as a natural antioxidant is revealed by comparing the characteristics of treated oil samples to the control. Important markers of oxidative stability and general oil quality are the chemical characteristics of the oil, namely the acid value (AV), peroxide value (PV), anisidine value (AnV), and total oxidation value (TOTOX). The control oil exhibited low AV and PV values, indicative of minimal degradation and high-quality standards. In contrast, the used cooking oil (UCO) displayed significantly higher AV and PV values, reflecting the accumulation of oxidative products and free fatty acids resulting from repeated thermal exposure during frying. This supports studies in the literature that highlight the substantial deterioration of oil quality caused by extended heating, which is typified by an increase in free fatty acids and oxidation products that have an adverse effect on flavor and nutritional value [17, 18].

These chemical characteristics changed noticeably when different quantities of dehydrated orange peel were added. For example, the T1 treatment (5 g/100 mL) had the greatest AV and PV, indicating a possible pro-oxidant impact at lower doses, which might be related to a lack of antioxidant ability to effectively combat oxidative processes. On the other hand, these values were significantly reduced at higher doses (T2, T3, and T4), suggesting that the antioxidant qualities of orange peel became more noticeable at higher concentrations. This result is in line with earlier research that shown that by scavenging free radicals and preventing lipid peroxidation, natural antioxidants can greatly improve oxidative stability [19, 20].

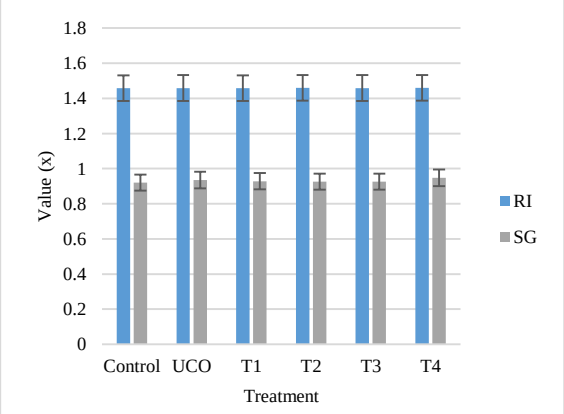
Furthermore, the anisidine value and TOTOX values followed similar trends, reinforcing the notion that higher concentrations of orange peel can mitigate secondary oxidation processes. The iodine value remained relatively stable across treatments, suggesting that the unsaturation levels of the oils were preserved despite the addition of orange peel. This stability is crucial for maintaining oil quality, as it indicates that beneficial unsaturated fatty acids are retained even when subjected to treatments aimed at improving oxidative stability [21].

Overall, the findings of the chemical analysis show that dehydrated orange peel has the potential to be a practical natural addition for improving the stability and quality of used cooking oil. By effectively reducing oxidation markers while preserving desirable fatty acid profiles, dehydrated orange peel not only improves oil quality but also promotes sustainable practices by utilizing food waste as a functional ingredient. Future research should continue to explore optimal treatment conditions and combinations with other natural antioxidants to further enhance oil stability and quality.

Physical Attributes

Refractive Index (RI) and Specific Gravity (SG)

The little alterations in refractive index (RI) and specific gravity (SG) suggest that the treatment had a negligible impact on the oil's physical qualities, which is a significant factor for practical applications (Fig 2). The antioxidant properties of citrus peels are well-established, with research indicating that phenolic components, including flavonoids and other antioxidants, significantly contribute to the oxidative stability of oils [1, 14, 16]. The findings of this investigation substantiate the concept that elevated levels of dehydrated orange peel might significantly diminish oxidation indicators in used frying oil, presenting a viable natural approach for enhancing oil quality and prolonging its usefulness. The results enhance the existing literature supporting using natural antioxidants from food waste, such as orange peels, to reduce the deterioration of cooking oils and enhance food safety and quality.



Orange peel concentrations in the treated oil samples are indicated by the letters T1, T2, T3, and T4; RI stands for Refractive Index, SG for Specific Gravity, and UCO for Used Cooking Oil.

Figure 2. Physical properties of used frying oil subjected to different quantities of dried orange peel.

The facts shown in Figures (1) and (2), when analyzed concerning the current literature, underscore the intricate relationships between the content of dried orange peel and the oxidative stability of used frying oil. Although lower concentrations may bring advantageous

chemicals, they may also intensify oxidation processes, as seen by the elevated AV and PV in T1. Conversely, higher quantities (T2, T3, and T4) have more advantageous antioxidant action, diminishing oxidation indicators while preserving the oil's physical qualities. These findings support sustainable food processing methods by demonstrating the potential of dried orange peel as a natural antioxidant to enhance the stability and quality of used frying oils [14, 21–23]. To maximize the benefits of natural antioxidants in cooking oils, more research is required to improve concentration and application methods.

The specific gravity (SG) and refractive index (RI) of the treated oils offer important information on the physical properties of the oil samples and how the addition of dehydrated orange peel has changed them. One important metric that shows the composition and purity of the oil is the RI. The RI values for the treated samples and control oil in the current investigation varied very little, suggesting that the addition of dehydrated orange peel had no discernible effect on the oils' optical characteristics. The treated oils' RIs varied from 1.4589 to 1.45935, whereas the control oils was 1.45835. This stability in RI suggests that the functional components in orange peel do not interfere with the oil's inherent optical characteristics, which is important for maintaining consumer acceptance and quality perception.

In a similar vein, measurements of specific gravity (SG) showed minor differences between samples, with values ranging from 0.921 for the control to 0.948 for T4. The addition of solid ingredients from the dehydrated orange peel, which might result in a denser oil matrix, may be the cause of the rise in SG in treated oils. These results are in line with other research showing that natural additives can affect physical characteristics without significantly changing them. For instance, research has shown that the SG of oils can change due to the presence of emulsifiers or other additives, impacting their behaviour during cooking and storage. The minor changes observed in RI and SG suggest that while dehydrated orange peel effectively enhances oxidative stability and improves chemical properties, it does so without compromising essential physical attributes. This is particularly relevant for applications in food processing, where maintaining desirable physical properties is crucial for both functionality and consumer appeal. Future studies could further explore how varying concentrations of orange peel affect these physical attributes over extended periods or under different storage conditions, providing deeper insights into their long-term effects on oil quality [18].

In conclusion, this study's characterisation of RI and SG shows how dehydrated orange peel may be utilized as a natural addition to enhance the quality of used cooking oil while maintaining its physical characteristics. As consumers increasingly seek healthier and more sustainable food options, incorporating such natural ingredients into cooking oils may offer a viable solution for enhancing oil stability without compromising quality or safety.

Alterations in fatty acid composition

Significant changes in the fatty acid content of spent frying oil exposed to varying concentrations of dried orange peel are seen in Table (1). These findings are consistent with other studies looking at how natural antioxidants derived from plants affect the longevity and quality of cooking oils. A notable finding is the detection of lauric acid (C12:0) in the used oil sample, which was absent in both the control and treated oils. Lauric acid is a medium-chain saturated fatty acid linked to possible health advantages, including antibacterial characteristics and cholesterol-lowering actions. The lack of the compound in the treated oils indicates that the dried orange peel may have affected its breakdown or transformation into other fatty acids throughout the treatment procedure.

Table 1. Changes in the fatty acid content of used frying oil after varying amounts of dried orange peel were added.

Fatty acid sign	Control	UCO	T1	T2	T3	T4
	Area (%)					
C12:0	ND	0.38 ±0.09	ND	ND	ND	ND
C14:0	1.11 ±0.05	0.96 ±0.11	1.00 ±0.04	1.02 ±0.05	1.06 ±0.03	1.02 ±0.09
C16:0	40.99 ±0.55	40.26 ±0.56	41.15 ±0.87	40.11 ±0.75	40.59 ±0.88	40.65 ±0.55
C18:0	4.71 ±0.17	4.37 ±0.17	4.44 ±0.35	4.55 ±0.15	4.45 ±0.26	4.89 ±0.14
C18:1	42.6 ±0.72	42.66 ±0.88	42.89 ±0.94	42.82 ±0.78	43.25 ±0.96	42.42 ±0.46
C18:2	10.05 ±0.19	10.62 ±0.14	9.95 ±0.23	9.81 ±0.25	9.96 ±0.38	9.85 ±0.11
C18:3	ND	0.27 ±0.06	ND	0.24 ±0.02	ND	0.63 ±0.05
C20:0	0.54 ±0.12	0.48 ±0.09	0.57 ±0.22	1.45 ±0.07	0.69 ±0.06	0.54 ±0.02

"ND" stands for "not detected." Lauric acid is represented by C12:0, palmitic acid by C16:0, stearic acid by C18:0, oleic acid by C18:1, linoleic acid by C18:2, α-linolenic acid by C18:3, and arachidic acid by C20:0.

With very little variations, the saturated fatty acid contents of myristic acid (C14:0) and palmitic acid (C16:0) were consistent throughout all samples. Perhaps as a result of the higher concentration of dried orange peel employed in the T4 treatment, stearic acid (C18:0) increased somewhat. Oleic acid (C18:1) showed a little rise in unsaturated fatty acids in the treated oils, particularly in T3. This finding is consistent with studies suggesting that natural antioxidants might increase monounsaturated fatty acid stability [24]. The

polyunsaturated fatty acid linoleic acid (C18:2) showed a little decline during the course of the treatments, which may have been caused by its susceptibility to oxidation. The addition of the omega-3 polyunsaturated fatty acid α-linolenic acid (C18:3) to the T2 and T4 treatments constituted a major change. The absence of α-Linolenic acid in the utilized oil sample suggests that the dried orange peel may have made it easier to produce or preserve it during these procedures. Due to its potential health benefits, such as lowering inflammation and improving cardiovascular health, α-Linolenic acid is considered a beneficial fatty acid. While remaining relatively low in the other samples, the T2 treatment showed a significant rise in the arachidic acid (C20:0) content. Long-chain saturated fatty acids like arachidic acid have been studied for potential health advantages, such as lowering the risk of cardiovascular disease.

According to the results, adding dried orange peel might change the fatty acid composition of used frying oil and perhaps improve its nutritional profile by increasing fatty acids that are favorable, including α-linolenic acid. The observed changes might be attributed to orange peel's antioxidant properties, which could help keep certain fatty acids stable and prevent them from breaking down when fried [25]. The findings of this study add to the body of knowledge about the use of fruit peels as natural antioxidants to raise the stability and quality of cooking oils. The results suggest that dried orange peel might be a useful natural supplement to enhance the fatty acid content of used cooking oil, perhaps boosting its nutritional value.

Photometric Colour Index (PCI)

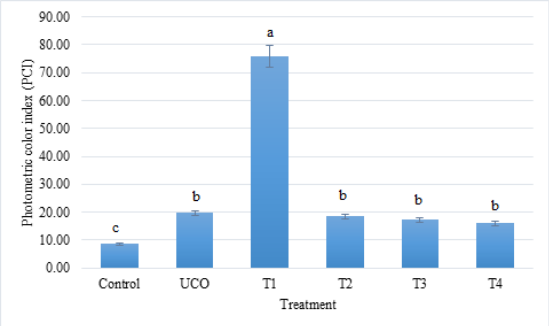
The findings concerning the photometric colour index (PCI) of used frying oil treated with dehydrated orange peel indicate substantial alterations in oil colour resulting from the treatments. The reference oil had a PCI of 8.52, signifying a light hue, but the utilised oil presented a significantly elevated PCI of 19.63, indicative of the buildup of degradation byproducts and contaminants from the frying procedure (Fig 3). This corresponds with research indicating that oil colour might signify quality, with deeper hues being linked to oxidative deterioration and the presence of undesirable components, including free fatty acids and polymerised products.

The notable rise in PCI to 75.82 for the T1 treatment (5 g/100 ml of orange peel) indicates that this concentration adds pigments or induces processes that markedly modify the oil's colour. This discovery aligns with the study conducted by O'Keefe and Pike [26], which demonstrates that the photometric colour index is affected by oil-soluble pigments, such as carotenoids and chlorophyll, that may colour oils. The use of pigments derived from dried orange peel may enhance the aesthetic quality of the oil. However, it also prompts apprehensions over the possibility of excessive darkening [27]. Notably, increased concentrations of orange peel (T2, T3, and T4, at 10, 15, and 20 g/100 ml, respectively) yielded PCI values (18.43, 17.29, and 16.09) that approximated those of the used oil, signifying no further darkening. This indicates a threshold effect in which lesser amounts of orange peel markedly darken the oil, yet greater concentrations do not intensify this impact. These phenomena may be ascribed to the saturation of pigment incorporation at elevated doses, when the advantages of antioxidant qualities may surpass the visual effects of colour alteration [28].

The results underscore the need to adjust the concentration of dehydrated orange peel to improve oil quality while maintaining its aesthetic appeal. The hue of cooking oils is essential, serving as both a quality indicator and a factor affecting customer acceptability and marketability. Prior research indicates that consumers often link lighter-coloured oils with superior quality and freshness, necessitating a compromise between antioxidant effectiveness and visual appeal [29, 30, 31]. These results improve our understanding of the potential use of natural antioxidants, especially those found in fruit peels, to improve the quality of used frying oils while maintaining desirable sensory qualities. The research endorses the prospective use of dehydrated orange peel as a natural addition in the food sector, along with the increasing inclination towards plant-based components to improve food quality and safety.

Viscous behaviour

The evaluation of the viscosity behaviour of oil samples in this study offers important new information on how dehydrated fruit peel treatments affect the physical characteristics of used frying oil. The control oil demonstrated a characteristic reduction in viscosity with escalating stirring speed, commencing with 220 cP at 0.3 rpm and diminishing to around 64.4 cP at 60 rpm (Fig 4). This pattern aligns with the anticipated behaviour of oils, whereby viscosity diminishes as the shear rate escalates, a characteristic of Newtonian fluids. The used oil exhibited a reduced viscosity compared to the control, stabilising at 76-77 cP at elevated speeds. This finding indicates that the repeated heating and frying processes may have modified the oil's composition, resulting in a decrease in its viscosity, corroborated by literature that demonstrates frying can significantly alter the physical properties of oils, including viscosity, due to thermal degradation and the formation of polymerised compounds from triglycerides [32, 33].



Orange peel concentrations in the treated oil samples are indicated by the letters T1, T2, T3, and T4; UCO for Used Cooking Oil.

Figure 3. Trends in the photometric colour index (PCI) of oil samples.

The treatments using dehydrated fruit peels (T1 to T4) had diverse impacts on viscosity, with T3 and T4 yielding the lowest viscosities over the speed spectrum. The decrease in viscosity at higher concentrations of fruit

peels suggests that including these natural antioxidants may promote a more fluid oil consistency, possibly improving the oil's efficacy during frying. Prior research has shown that the integration of natural additives might affect the rheological characteristics of oils, with some additions reducing viscosity by inhibiting the production of high molecular weight compounds during thermal degradation [34, 35]. The observed trend indicating that increased concentrations of dried orange peel result in decreased viscosities may be ascribed to the bioactive chemicals in the peels, which may interact with the oil matrix, modifying its flow characteristics. This aligns with the results of Sahasrabudhe et al. [33], which indicated that the viscosity of frying oils diminishes with the incorporation of certain natural components, thereby enhancing oil drainage and absorption properties during frying operations.

Furthermore, the reduced viscosity of treated oils may beneficially influence their frying efficacy by improving heat transmission and decreasing the oil's flow resistance, which is essential for optimal frying. The viscosity of frying oils is a crucial determinant of oil absorption and drainage rates, as well as the overall quality of fried items [35, 36]. The capacity of dehydrated orange peel treatments to reduce viscosity while preserving or augmenting the oil's antioxidant qualities offers a viable approach for boosting the quality and durability of used frying oils. The findings demonstrate that treatments with dehydrated orange peels may significantly modify the viscosity characteristics of utilised frying oil, with increased concentrations resulting in reduced viscosities. This conclusion is corroborated by existing research that highlights the influence of natural additions on the physical characteristics of cooking oils, therefore improving their performance and stability during frying. The ramifications of these findings are significant for food quality and safety, indicating that natural antioxidants may enhance oil attributes without undermining its functional capabilities.

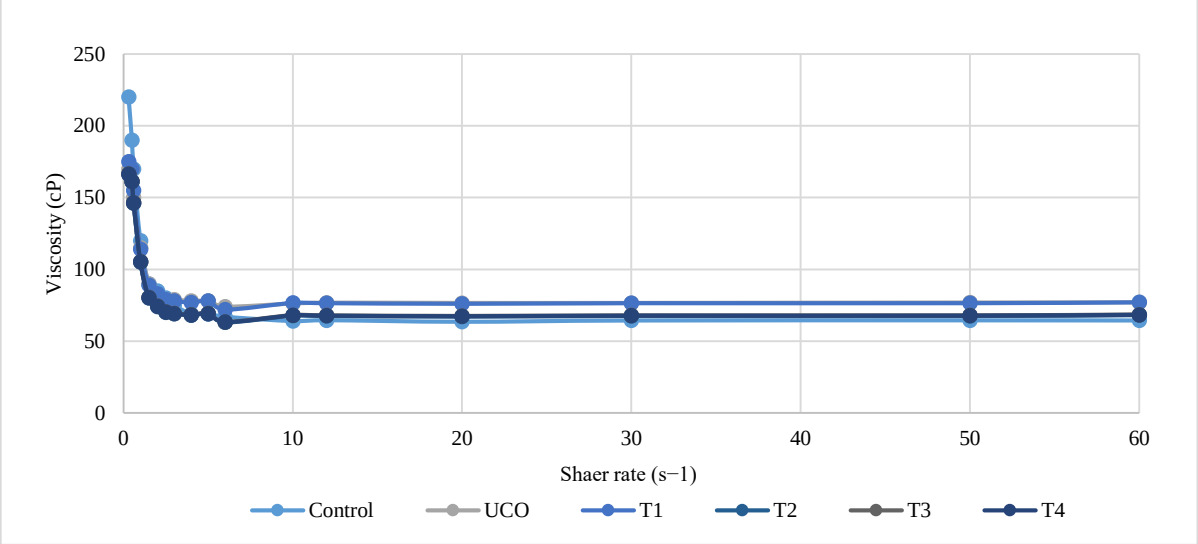


Figure 4. Viscosity behaviour of oil samples.

Limitations, Future Perspectives, and Challenges

It is important to recognize a number of limitations even if this study shows how dehydrated orange peel may be utilized as a natural antioxidant to improve the stability and quality of used cooking oil. The variation in orange peel composition, which can be impacted by elements including orange variety, location, and processing techniques, is one major drawback. These variances might have an impact on the bioactive chemicals' concentration and effectiveness, producing varying outcomes from various orange peel batches. Further investigation is required to examine the sensory qualities of fried foods and consumer approval of oils treated with orange peel, as the study mainly concentrated on certain oxidative indicators and physical characteristics.

Looking ahead, future studies should aim to optimise extraction methods and concentrations of orange peel to maximise antioxidant efficacy while minimising any adverse effects on oil colour and viscosity. Investigating the synergistic effects of combining orange peel with other natural antioxidants could also enhance oil stability. Furthermore, challenges remain in scaling up the application of dehydrated orange peel in commercial food processing environments. Addressing issues related to cost-effectiveness, standardisation of treatment protocols, and regulatory considerations will be essential for integrating this natural additive into mainstream cooking oil production. Overall, continued research in this area holds promise for developing sustainable practices that leverage food waste while improving oil quality and safety.

Conclusion

The findings of this study demonstrate how dehydrated orange peel works as a natural antioxidant to enhance the stability and quality of used cooking oil. According to the chemical investigations, higher concentrations of orange peel (10–20 g/100 mL) significantly reduced oxidation markers such as acid value, peroxide value, anisidine value, and Totox value while simultaneously raising levels of beneficial fatty acids like α-linolenic acid. The iodine value's constancy

during treatments shows that the oils' unsaturation levels were preserved, which is crucial for maintaining oil quality. In order to satisfy consumer preferences for visual aesthetics, the photometric colour index revealed a threshold effect, whereby higher concentrations of orange peel maintained a colour similar to untreated used oil while lower amounts darkened the oil. According to viscosity research, higher orange peel concentrations led to lower viscosities, which may have improved the oil's frying performance by encouraging heat transfer and lowering flow resistance. This study improves food quality and sustainability by providing important new information on the use of dried orange peel as a natural additive in cooking oils. The results support the growing trend of employing plant-based waste materials in food processing, which calls for more research to improve extraction methods and concentrations for widespread use in the food industry.

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