



Enhancing Oxidative Stability of Palm Olein Oil Using Yemeni Red Onion Peels Extract (*Allium cepa* L.) During Deep-Frying

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ABSTRACT

This study evaluated the antioxidant potential of Yemeni red onion peels (YROP) extract in enhancing the oxidative stability of refined, bleached, and deodorized palm olein (RBDPO) Oil under deep-frying conditions (170–180°C for 25hours). The extract, applied at 200 and 400ppm, was compared to the synthetic antioxidant TBHQ (100ppm). At 400ppm, the extract effectively reduced free fatty acids and peroxide values by over 20%, preserved oil color, and achieved an oxidative stability index (OSI) of 15.20hours, close to TBHQ (17.53hours) and superior to untreated oil (10.25hours). Antioxidant activity (49.05% DPPH inhibition) and total phenolic content (37.36mg GAE/g DW) supported its effectiveness. These findings indicate that the YROP extract demonstrates notable antioxidant potential, enhancing oil quality and shelf life, while promoting sustainable utilization of agro-industrial waste.

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1. INTRODUCTION

Vegetable oils are a vital dietary source of energy, essential fatty acids, and fat-soluble vitamins [1]. Refined, bleached, and deodorized palm olein (RBDPO) oil is widely used for frying because of its oxidative stability and affordability [2, 3]. Nevertheless, repeated heating at high temperatures (160–180°C) accelerates lipid oxidation, leading to the formation of harmful compounds that compromise oil quality and pose potential health risks [4–7]. Because oxidative stability directly influences shelf life, it is commonly evaluated using the Rancimat method, which is strongly correlated with phenolic content [8]. To delay oxidation, synthetic antioxidants such as BHA, BHT, and TBHQ are often applied; however, their potential hepatotoxic and carcinogenic effects have raised serious safety concerns [9–11]. Consequently, growing interest has been directed toward natural alternatives. In this regard, onion (*Allium cepa* L.) peels, par-

ticularly red varieties, are recognized as rich sources of phenolic compounds, especially quercetin, which confers strong antioxidant activity [12, 13]. Although constituting nearly 10% of the bulb, these peels are often discarded and remain underutilized in Yemen despite their high quercetin content [14–17]. Previous studies have demonstrated the efficacy of onion peels extract in enhancing the oxidative stability of edible oils. For instance, [18, 19] reported significant improvements in soybean oil stability during both storage and heating, while [20] observed similar protective effects in a soybean–sunflower oil blend. Likewise, [21] showed that onion peels helped preserve the quality of cooking mustard oil, and [11] confirmed their effectiveness in stabilizing refined palm olein (RBDPO) oil. Moreover, [22] demonstrated that onion peel extracts suppress the accumulation of harmful oxidation products in commercial seed oils. Collectively, these findings highlight onion peels extract as a natural, safe, and eco-friendly alternative to synthetic antioxidants, in



some cases even outperforming BHT [11, 21, 23]. Based on this background, the present study investigated the antioxidant potential of Yemeni red onion peel (YROP) extract at concentrations of 200 and 400ppm, compared to TBHQ 100ppm, using Rancimat analysis, DPPH radical scavenging, total phenolic content, and key oil quality indices.

2. MATERIALS AND METHODS

2.1. MATERIALS

Yemeni red onion (*Allium cepa* L.) and potato (*Solanum tuberosum* L.) (Barakah) peels were obtained from a local market in Ibb Governorate, Yemen, Brazil. (RBDPO) Oil was obtained from the Yemen Company for Ghee and Soap Industry (YCGSI), Taiz, Yemen. The onion peels were hand-cleaned to remove impurities, thoroughly washed with distilled water, and air-dried at ambient temperature. The dried samples were then stored in opaque plastic containers and in a deep freezer at -20 °C until further analysis. All reagents and solvents used in this study were of high purity and suitable for HPLC. These included absolute ethanol ($\geq 99.9\%$), DPPH (2,2-diphenyl-1-picrylhydrazyl), gallic acid, Folin-Ciocalteu reagent, sodium carbonate, and aluminum chloride, all from Sigma-Aldrich (USA). TBHQ 2-(1,1-Dimethylethyl)-1,4-benzenediol, with a food purity of 99.8%, was used as a synthetic antioxidant. This compound was manufactured by Crystal Quinone (India) and was supplied by (YCGSI) Taiz, Yemen.

2.2. METHODS

2.2.1. Traditional extraction procedure

A modified conventional extraction adapted from [24] was applied to (YROP) extract. Finely ground, dried peels (10g) were extracted with 300mL of 80% ethanol (1:30 w/v) using magnetic stirring (Stuart SB 162-3, Bio-Cote®, UK) at 80rpm for 120min at $25 \pm 2^\circ\text{C}$. The mixture was centrifuged (Heraeus Sepatech Medifuge, Germany) at 4000rpm for 15min, and the supernatant was filtered through Whatman No.1 paper. The residue was re-extracted twice under the same conditions. Combined filtrates were adjusted to 1000mL, concentrated using a rotary evaporator (BUCHI, Switzerland), and dried at 45 °C. The extract was stored in airtight glass containers at 20- °C until analysis.

2.2.2. Preparation of Oil Samples

Oil samples were prepared by dissolving 1.0 g and 2.0 g of dried YROP extract in 50mL of absolute ethanol to obtain 200 and 400ppm concentrations, respectively, following [25] with slight modifications. Each solution was added to 5 L of RBDPO Oil with continuous stirring and then heated to 80 °C to evaporate ethanol. A

100ppm TBHQ sample was prepared by dissolving 0.5 g in 5000 g of oil at 80 °C, based on [26]. All samples were immediately used for antioxidant testing.

2.2.2.1 Experimental treatments were as follows:

- 2.2.2.1 Control (RBDPO Oil without additives)
- 2.2.2.2 RBDPO Oil + 400ppm YROP extract
- 2.2.2.3 RBDPO Oil + 200ppm YROP extract
- 2.2.2.4 RBDPO Oil + 100ppm TBHQ

2.2.3. Evaluation of Antioxidant Activity During Deep-Frying of Potatoes in RBDPO Oil Enriched with Tested Extracts

Antioxidant activity of the tested extracts was evaluated by deep-frying of "Baraka" potato slices in RBDPO Oil enriched with different antioxidants. Frying was performed using an electric deep fryer (Oleocean Tefal, France) at $170\text{--}180 \pm 5^\circ\text{C}$ for 25hours, simulating household and industrial conditions [27]. Oil samples were collected at 0, 5, 10, 15, 20, and 25hours to assess the thermal oxidation. Experimental treatments. Oxidative stability and physicochemical properties were monitored to compare the antioxidant performance under thermal stress.

2.2.4. Evaluation of Oxidative Stability (OSI) of RBDPO Oil Enriched with Tested Extracts Using the Rancimat Method

The oxidative stability index (OSI) of the phenolic-rich YROP extract was determined following the AOCS Method Cd 12b-92 [28] with modifications based on [29]. Phenolics were extracted using 70% ethanol, and 50mL of the same solvent was added to each extract according to [25]. Extracts were mixed with 100mL of RBDPO Oil to prepare different experimental treatments. The residual ethanol was removed by rotary evaporation (BUCHI, Switzerland) at 40 °C. Oil samples (3.00 ± 0.01 g) were analyzed using a Rancimat (Metrohm, Switzerland) at 120 °C with a dry airflow of 20 L/h. Volatile oxidation products were detected by conductivity in deionized water ($0\text{--}400\mu\text{S}/\text{cm} \pm 0.1$), and the OSI was recorded at the inflection point of the conductivity curve. The tests were performed in triplicates.

2.2.5. Determination of total phenolic content (TPC)

Total phenolic content (TPC) was estimated using the Folin-Ciocalteu method [30] with modifications. Briefly, 100 μL of extract was diluted to 3mL with deionized water and mixed with 0.5mL Folin-Ciocalteu reagent for 3 min, after 2mL of 20% Na_2CO_3 was added and incubated for 1h in the dark at room temperature. The absorbance was measured at 725 nm using a Shimadzu UV-Vis spectrophotometer (UV-1900i, Japan). Gallic acid standards (5–30 mg/mL) were used to establish a calibration curve ($y=0.0642x + 0.0244$; $R^2=0.9986$). TPC was calculated as milligram gallic acid equivalents per 100 g sample (mg GAE/100 g DW).

2.2.6. Determination of total antioxidant activity (TAA)

A free radical scavenging assay was performed to determine the antioxidant activity of (YROP) extract. The same extract was used for the DPPH assay.

2.2.6.1 DPPH Radical Scavenging Activity Assay

Antioxidant activity was measured using the DPPH assay as described previously [31]. Briefly, YROP extract 0.5mL of YROP extract at various concentrations was mixed with 3mL absolute ethanol and 50 μ M DPPH, then incubated in the dark for 30 min. The absorbance was read at 517 nm using a Shimadzu UV-Vis spectrophotometer (UV-1900i, Japan). DPPH solution without antioxidants served as a control. The percentage of DPPH radical scavenging activity was calculated using the formula: The percentage of DPPH radical scavenging activity is calculated using the formula: Antioxidant Activity (%) = [(Absorbance of Control - Absorbance of Sample) / Absorbance of Control] * 100.

2.2.7. Tested Chemical and Physical Quality Characteristics

Oil samples were analyzed in triplicate for quality parameters, including:

2.2.7.1 Chemical Oxidation Indices:

2.2.7.1.1 Peroxide Value (PV) by AOCS Cd 8b-90 [32],

2.2.7.1.2 p-Anisidine Value (p-AV) by AOCS Cd 18-90 [33],

2.2.7.1.3 Total Oxidation Value (TOTOX) calculated as $TOTOX = (2 \times PV) + p-AV$ [30],

2.2.7.1.4 Free Fatty Acid (FFA) content by AOCS Ca 5a-40 [34].

2.2.7.2 Physical Indices:

2.2.7.2.1 Color (Lovibond) measured by AOCS Cc 13j-97 [35].

2.2.8. Statistical Analysis

The data were analyzed using IBM SPSS Statistics (version 25). Descriptive statistics were used to summarize categorical variables. Levene's test assessed variance homogeneity. One-way ANOVA was used to evaluate group differences, followed by LSD or Tamhane's T2 tests depending on variance equality. Statistical significance was set at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. EFFECT OF STUDIED ANTIOXIDANT EXTRACTS ON THE OXIDATIVE STABILITY OF RBDPO OIL DURING DEEP-FRYING

The stability of frying oils during repeated use is a critical concern because of their susceptibility to oxidative degradation, which leads to the formation of free fatty acids (FFA) and increases in peroxide value (PV),

p-anisidine value (p-AV), and total oxidation value (TOTOX). In addition, the color changes measured by the Lovibond scale serve as further indicators of thermal degradation. Several studies have confirmed the protective role of natural antioxidants in mitigating these detrimental changes. For instance, [11] reported that red onion peel extract, which is rich in flavonoids and polyphenols, significantly enhanced the oxidative stability of refined, bleached, and deodorized palm (RBDPO) oil, effectively reducing PV, p-AV, and TOTOX compared with both untreated oil and oil treated with the synthetic antioxidant BHT, particularly at a concentration of 9%. Our findings are consistent with those of [25] regarding the type of oil used (RBDPO) and the application of natural extract concentrations (200 and 400ppm), in addition to the use of the synthetic antioxidant TBHQ, which effectively reduced both FFA and PV, thereby confirming its antioxidant potential. However, the difference lies in the choice of natural extract: [25] employed green tea leaf extract, whereas our study used Yemeni red onion peel extract. Similarly, [36] reported that green tea extract and γ -oryzanol exerted protective effects by reducing oxidative degradation of unsaturated fatty acids during frying. Furthermore, our results are consistent with those of [27], who investigated deep-fat frying of potatoes using RBDPO Oil supplemented with TBHQ alone. Nevertheless, the distinction between the two studies lies not only in our inclusion of red onion peel extract as a source of natural antioxidants for comparison with synthetic antioxidants but also in the frying conditions. While [27] conducted only seven frying cycles, each lasting no longer than 15 min (a total of less than two hours), our study extended to approximately 100 frying cycles, performed for 5 hours daily over 5 consecutive days, corresponding to a total of 25 hours of repeated frying. Taken together, these findings support the effectiveness of Yemeni red onion peel extract (200 and 400ppm) as a promising natural alternative to synthetic antioxidants such as TBHQ for preserving the quality of RBDPO Oil under thermal stress conditions.

Statistical analysis using two-way analysis of variance (ANOVA) was performed to evaluate the effects of treatment (200 and 400ppm (YROP) extract, 100ppm TBHQ, and control) and frying duration (one–five days) on the physicochemical parameters under study. Homogeneity of variance was assessed using Levene's test, followed by appropriate post-hoc tests (T2 or Tamhan's LSD test) at a significance level of $p < 0.05$. Significant interaction effects indicated changes in antioxidant performance over time. The 400ppm extract consistently maintained an increased red color ($p < 0.001$), which was attributed to phenolic pigments such as anthocyanins. The TBHQ extract showed the lowest FFA and PV values during early frying, which subsequently declined, while the 400ppm extract showed persistent peroxide stability throughout



the frying period. For TOTOX, TBHQ was initially more effective, but the 400ppm extract improved it in the later stages. Subsequent comparisons revealed significant differences between the treatment and control groups, particularly with regard to red color, TOTOX, FFA, and PV. No significant differences were observed between the 200 and 400ppm extraction treatments for some parameters. Overall, the 400ppm red onion peel extract demonstrated promising antioxidant activity, effectively preserving oil quality during prolonged frying and offering a natural alternative to synthetic antioxidants.

3.1.1. Evaluated Chemical and Physical Quality Properties

3.1.1.1 Chemical Indices for Oxidation Assessment

3.1.1.1.1 free fatty acids (FFA)

As presented in [Table 1], antioxidant treatment significantly influenced free fatty acid (FFA) accumulation during repeated frying cycles. Red onion peel extract at 400ppm consistently exhibited the most effective suppression of FFA formation, maintaining lower and more stable levels, indicative of enhanced antioxidant capacity and thermal stability. The 200ppm extract also reduced FFA levels compared to the control, albeit with less consistency. TBHQ at 100ppm showed the lowest initial FFA values, demonstrating a strong short-term antioxidant activity that diminished over time. The control group, which lacked antioxidants, experienced the highest increase in FFA levels, reflecting accelerated triglyceride hydrolysis and oil deterioration. These results are consistent with previous research indicating that natural antioxidants reduce FFA buildup during frying [36], repeated frying elevates FFA underscoring the need for antioxidants and thermal management [37], and lipid hydrolysis is closely linked to oxidative degradation in heated oils [27, 38]. The results of this study differ from those of previous reports, as the FFA values reached 0.321 and 0.489 at 400 and 200ppm of (YROP) extract, respectively, compared to 0.259 with TBHQ 100ppm and 0.407 in the control. This demonstrates that the extract effectively limited the release of free fatty acids during deep-frying, although the differences between the concentrations were relatively small. In contrast, Prameswari et al. [11] reported much lower values 0.00–0.02% when using high extract concentrations of 3–12% or BHT 0.01%, with untreated oil measuring 0.01 ± 0.00 . This variation is attributed to methodological differences, including the onion type (*Allium cepa* L. vs. *Allium ascalonicum*), oil type (RBD palm olein oil under deep-frying vs. RBD palm oil under mild heating), heat intensity (170–180 °C for five hours and over a period of five days vs. 60 °C for 24 hours), and extract concentrations (200–400ppm vs. 3–12%). Therefore, the higher values observed in this study do not indicate reduced efficacy of the Yemeni extract, but rather reflect the severity of the

experimental conditions. Both studies agree on the promising role of onion peels as a natural antioxidant source in limiting oxidative deterioration and enhancing oil stability. In summary, 400ppm red onion peel extract is a sustainable and thermally stable antioxidant that effectively delays FFA accumulation and preserves oil quality throughout the frying cycles.

3.1.1.1.2 Peroxide Value (PV)

As shown in [Table 1], treatment with 400ppm red onion peel extract consistently maintained lower peroxide values (PV) throughout all frying cycles, demonstrating the strong suppression of lipid hydroperoxides, which are primary indicators of oxidative degradation. This concentration provided the most stable and sustained antioxidant protection, outperforming other treatments. The 200ppm extract showed moderate PV reduction compared to the control, but with less durability. The synthetic antioxidant TBHQ (100ppm) initially yielded the lowest PV, indicating strong early efficacy; however, its effectiveness declined markedly over time. The control group exhibited a continuous increase in PV, reflecting the natural oxidation during high-temperature frying without antioxidant protection. These results are consistent with the reported increases in PV with frying cycles [27], and the effectiveness of natural antioxidants such as onion peel phenolics in mitigating hydroperoxide formation under heat stress [37]. Additionally, the importance of antioxidants and proper frying conditions in controlling PV has been highlighted [37], with oil degradation linked to elevated PV during prolonged heating [39]. The results of this study show that peroxide values were 28.533 and 28.136 meq O₂/kg for (YROP) extract at 400 and 200ppm, respectively. In comparison, the values for TBHQ 100ppm and control were 33.967 and 36.605 meq O₂/kg respectively. These findings contrast with a study by Prameswari et al. [11], which reported much lower peroxide values (6.65–17.29 meq/kg) when using high extract concentrations (3–12%) or BHT (0.01%), in that study, the untreated oil measured 30.0 ± 4.00 meq/kg. This discrepancy is attributed to the methodological differences previously discussed in the Free Fatty Acids (FFA) section. Therefore, the differences in values did not diminish the efficacy of the Yemeni extract; rather, they reflected the intensity of the experimental conditions. Both studies confirmed the promising role of red onion peel as a natural antioxidant source for improving oil stability. Overall, 400ppm red onion peel extract demonstrated superior and consistent antioxidant performance, offering a promising natural alternative to synthetic additives for preserving frying oil stability.

3.1.1.1.3 Para-anisidine Value (p-AV)

As shown in [Table 1], frying oil samples treated with 400ppm red onion peel extract consistently exhibited



Table[1]: Impact of Antioxidant Treatments on Frying Oil Quality Parameters During Five Consecutive Days of Deep-Frying

Treatment	Day	Red Color (Lovibond Units) Mean ± SD	FFA (%) Mean ± SD	PV (meq O ₂ /kg) Mean ± SD	p-AV Mean ± SD	TOTOX Mean ± SD
400ppm	Day 1	11.17 ± 0.06 ^a	0.125 ± 0.003 ^b	9.826 ± 0.021 ^b	13.536 ± 0.007 ^b	36.898 ± 0.034 ^c
200ppm		6.53 ± 0.06 ^b	0.127 ± 0.002 ^b	14.713 ± 0.030 ^a	16.956 ± 0.007 ^a	48.625 ± 0.044 ^b
TBHQ100		6.23 ± 0.06 ^b	0.100 ± 0.002 ^c	3.276 ± 0.085 ^d	9.259 ± 0.013 ^d	21.795 ± 0.060 ^d
Without antioxidants		6.67 ± 0.06 ^b	0.126 ± 0.002 ^b	17.555 ± 0.019 ^c	18.178 ± 0.006 ^c	53.911 ± 0.029 ^a
400ppm	Day 2	11.13 ± 0.06 ^a	0.144 ± 0.003 ^b	15.512 ± 0.134 ^b	19.877 ± 0.065 ^b	55.264 ± 0.134 ^b
200ppm		7.33 ± 0.06 ^b	0.184 ± 0.004 ^a	16.633 ± 0.019 ^a	20.417 ± 0.036 ^a	57.467 ± 0.091 ^a
TBHQ100		7.57 ± 0.06 ^b	0.104 ± 0.001 ^c	16.189 ± 0.020 ^a	18.251 ± 0.014 ^c	52.690 ± 0.009 ^c
Without antioxidants		7.53 ± 0.06 ^b	0.200 ± 0.006 ^d	22.007 ± 0.081 ^c	21.507 ± 0.007 ^d	65.020 ± 0.073 ^d
400ppm	Day 3	11.17 ± 0.06 ^a	0.170 ± 0.003 ^b	24.128 ± 0.016 ^b	20.175 ± 0.014 ^b	64.478 ± 0.044 ^b
200ppm		7.63 ± 0.06 ^b	0.199 ± 0.003 ^a	21.308 ± 0.020 ^c	21.143 ± 0.003 ^a	63.594 ± 0.014 ^c
TBHQ100ppm		8.77 ± 0.06 ^c	0.107 ± 0.001 ^c	27.728 ± 0.019 ^a	19.060 ± 0.014 ^c	65.847 ± 0.009 ^a
Without antioxidants		8.73 ± 0.06 ^c	0.298 ± 0.005 ^d	28.290 ± 0.018 ^a	22.206 ± 0.100 ^d	72.701 ± 0.185 ^d
400ppm	Day 4	11.23 ± 0.06 ^a	0.193 ± 0.003 ^b	26.680 ± 0.020 ^b	21.635 ± 0.007 ^b	69.950 ± 0.034 ^b
200ppm		7.87 ± 0.06 ^b	0.247 ± 0.003 ^a	25.144 ± 0.020 ^c	22.038 ± 0.057 ^a	69.226 ± 0.133 ^c
TBHQ100ppm		9.17 ± 0.06 ^c	0.171 ± 0.001 ^c	30.125 ± 0.029 ^a	20.985 ± 0.007 ^c	72.096 ± 0.014 ^a
Without antioxidants		9.17 ± 0.06 ^c	0.371 ± 0.010 ^d	32.905 ± 0.013 ^d	23.352 ± 0.044 ^d	79.610 ± 0.075 ^d
400ppm	Day 5	11.77 ± 0.06 ^a	0.321 ± 0.003 ^b	28.533 ± 0.019 ^b	22.732 ± 0.001 ^b	73.996 ± 0.021 ^c
200ppm		8.07 ± 0.06 ^b	0.489 ± 0.001 ^a	28.136 ± 0.019 ^b	23.955 ± 0.010 ^a	76.045 ± 0.040 ^b
TBHQ100ppm		9.53 ± 0.06 ^c	0.259 ± 0.002 ^c	33.967 ± 0.020 ^a	21.538 ± 0.008 ^c	77.042 ± 0.037 ^a
Without antioxidants		9.67 ± 0.06 ^c	0.407 ± 0.001 ^d	36.605 ± 0.020 ^c	24.338 ± 0.148 ^d	85.280 ± 0.303 ^d

Notes:

- Values represent Mean ± SD (n = 3).
- Different superscript letters (a, b, c, d) within the same column and day indicate significant differences at p < 0.05 (LSD test).

Abbreviations:

- FFA = Free Fatty Acids (%).
- PV = Peroxide Value (meq O₂/kg).
- p-AV = p-Anisidine Value.
- TOTOX = Total Oxidation Value = (2×PV) + p-AV.
- Red color = Oil Color (Lovibond Units).

the lowest p-anisidine values (p-AV), indicating effective suppression of secondary oxidation products such as aldehydes and ketones. This antioxidant effect is likely due to the thermally stable phenolic compounds that inhibit lipid degradation at advanced stages. The 200ppm extract provided moderate protection, while TBHQ (100ppm) showed an initial efficacy that declined over time. The control group had the highest p-AV, reflecting extensive oxidative deterioration. These results align with those of previous studies, demonstrating the role of natural antioxidants in reducing p-AV and enhancing lipid stability [36], the correlation between oil degradation and p-AV increases [38, 39]. Although p-AV was not directly measured in [27], related oxidation trends were observed. The results of this study differ from those of previous reports, with p-anisidine values of 22.732 and 23.955 at 400 and 200ppm of (YROP) extract, respectively, compared to 21.538 with TBHQ (100ppm) and 24.338 in the control. This demonstrates that the extract contributed to reducing the formation

of secondary oxidation products (aldehydes) under deep-frying conditions, although the differences between concentrations were minimal. In contrast, Prameswari et al. [11] reported significantly lower values (3.54–7.23) when using higher extract concentrations (3–12%) or BHT (0.01%), with untreated oil at 18.52 ± 3.18. This variation is attributed to methodological differences outlined in the FFA section. Accordingly, the higher values in this study do not indicate reduced efficacy of the Yemeni extract but rather reflect the intensity of the experimental conditions, confirming the promising role of onion peels in limiting secondary oxidation and enhancing oil stability. Overall, 400ppm red onion peel extract offers a thermally stable, natural alternative to synthetic antioxidants by minimizing secondary oxidation during frying.

3.1.1.1.4 Total Oxidation Value (TOTOX)

As shown in [Table 1], the TOTOX values of a combined



measure of primary (PV) and secondary (p-AV) oxidation products were effectively reduced in oil samples treated with 400ppm red onion peel extract. This indicates a strong and sustained protection against oxidative deterioration during deep-fat frying. The 400ppm extract maintained consistently low TOTOX values throughout frying, outperforming the 200ppm extract, which showed moderate reduction. TBHQ (100ppm) initially lowered the TOTOX values; however, its effectiveness declined over time. The control samples exhibited a continuous increase in TOTOX, reflecting high oxidation susceptibility. These results align with previous studies reporting lower TOTOX with natural antioxidants [36], elevated TOTOX during repeated frying cycles [35], cumulative oxidative markers consistent with TOTOX progression [37], and related oxidation trends from increased PV and FFA levels [27]. Total oxidation values in this study reached 73.996 and 76.045 at 400 and 200ppm of (YROP) extract, respectively, compared with 77.042 with TBHQ (100ppm) and 85.280 in the control. This indicated that the extract effectively reduced the overall primary and secondary oxidation products under deep-frying conditions, surpassing TBHQ. In contrast, Prameswari et al. [11] reported much lower TOTOX values (15.92–43.44) for high extract concentrations (3–12%) or BHT (0.01%), with untreated oil measuring 67.23 ± 11.23 . This difference can be attributed to methodological variations described in the FFA section. Therefore, the higher values in this study reflect the severity of repeated deep-frying rather than the reduced efficacy of the Yemeni extract, with both studies agreeing on the extract's promising role as a natural antioxidant in improving oil stability. Overall, 400ppm red onion peel extract represents a thermally stable natural antioxidant offering prolonged protection against both primary and secondary oxidation, making it a promising alternative to synthetic antioxidants such as TBHQ.

3.1.1.2 Physical Indices

3.1.1.2.1 Red Color (Lovibond Units)

As shown in [Table1], frying oils treated with 400ppm red onion peel extract exhibited the highest red color intensity and greater stability throughout the frying cycles compared with other treatments. This stability is attributed to the rich phenolic content, particularly anthocyanins and flavonoids, which serve as natural pigments, antioxidants, and color stabilizers under thermal stress. The 200ppm concentration provided moderate protection, whereas TBHQ (100ppm) maintained a low initial color that declined with repeated frying. The control sample exhibited the greatest color loss. These findings align with those of [27], while similar effects were observed with plant-based antioxidants, such as green tea and lycopene in peanut oil [36]. Progressive color changes have also been noted in RBDPO Oil blends [37] and after multiple frying cycles [39].

Red color values in this study reached 11.77 and 8.07 at 400 and 200ppm of (YROP) extract, respectively, compared to 9.53 with TBHQ (100ppm) and 9.67 in the control. This demonstrates the effectiveness of the extract in preserving the red pigment of oil during deep-frying, with minor differences between the concentrations. In contrast, Prameswari et al. [11] reported narrow L, a, and b ranges (L: 32.50–33.17, a: -0.17–0.43, b: 32.50–33.17) regardless of the extract concentration or BHT addition, reflecting color stability under their experimental conditions. This discrepancy is partly attributed to differences in the color assessment methods, as this study employed **Lovibond Units**, whereas the previous study used the **Munsell Color Intensity Test**, along with other differences in onion type, oil type, heat intensity, and processing duration, as discussed in the FFA section. Therefore, the higher red color values in this study reflect the ability of the Yemeni red onion peel extract to preserve natural pigments under harsh deep-frying conditions, with both studies confirming its promising role in supporting color stability and improving oil quality. Overall, the 400ppm extract demonstrates dual functionality as a natural additive, improving both the color quality and oxidative stability.

Note: Blue Lovibond values remain negligible across all treatments. A minor, non-significant increase (up to 0.1) between Days 2 and 5 in some samples may indicate early thermal degradation, as noted in [39]. Due to their minimal impact, blue color values were excluded from the detailed analysis.

3.2. DETERMINATION OF OXIDATIVE STABILITY INDEX (OSI) OF EXTRACTS USING RANCIMET METHOD

The Oxidative Stability Index (OSI) of the red onion peel extract was determined using the Rancimat method, a standard technique for assessing oxidative resistance under accelerated thermal conditions. This method continuously measures volatile degradation products and provides a reliable indicator of the ability of the extract to delay lipid peroxidation. These results reflect the antioxidant effectiveness of the extract in enhancing the oil stability during heat exposure. A similar use of Rancimat was reported by [24] in evaluating factors affecting RBDPO Oil oxidation, confirming its reliability for testing antioxidant performance.

As shown in [Table2], the oxidative stability of the RBDPO Oil was evaluated using the Rancimat method. ANOVA revealed significant differences in induction time ($F=21867.59$, $p<0.001$). TBHQ at 100ppm exhibited the highest stability (17.53 ± 0.03 h), followed by red onion peel extract at 400ppm (15.20 ± 0.02 h) and 200ppm (15.11 ± 0.05 h), with the control showing the lowest (10.25 ± 0.04 h). Levene's test confirmed homogeneity

Table[2]: Oxidative Stability of RBDPO Oil Samples Treated with YROP Extract and TBHQ Assessed by the Rancimat Method

Treatments	Mean \pm SD
400ppm	15.20 \pm 0.02 ^a
200ppm	15.11 \pm 0.05 ^b
TBHQ 100ppm	17.53 \pm 0.03 ^c
Without antioxidants	10.25 \pm 0.04 ^d

Notes: Values are expressed as mean \pm standard deviation ($n = 3$). Different superscript letters (a–d) indicate statistically significant differences, between treatments at $p < 0.05$ (LSD test).

of variance ($p=0.276$), supporting the LSD post-hoc analysis. The superior efficacy of TBHQ aligns with its known potency, while the red onion peel extract demonstrated notable antioxidant activity, attributed to phenolic compounds, such as flavonoids and phenolic acids. These results are consistent with [38], highlighting that the phenolic content is a key factor in oil stability over fatty acid composition. For example, black cumin oil, rich in phenolics, showed high oxidation resistance, whereas linseed oil, which is high in polyunsaturated fatty acids, was more susceptible. A strong correlation ($r=0.89$) between the induction time and oxidation markers validated the reliability of the Rancimat test. Additionally, [38] reported the improved oxidative stability of red RBDPO Oil following free fatty acid reduction, emphasizing the role of pro-oxidant control and natural antioxidants.

The high phenolic content of (YROP) extract (37.36 ± 0.26 mg GAE/g DW) likely enhanced RBDPO Oil stability. Its DPPH scavenging activity further supports its role as an effective natural antioxidant and a promising alternative to synthetic additives such as TBHQ for improving oil shelf life and quality.

3.3. ANTIOXIDANT AND PHYTOCHEMICAL EVALUATION

The antioxidant capacity and phytochemical profile of (YROP) extract were evaluated using DPPH free radical scavenging and total phenolic content (TPC) assays. These results confirmed the significant contribution of these antioxidants to the bioactivity of the extract. A comparative summary of the findings is presented below.

Statistical analysis of total phenolic content (TPC), DPPH scavenging activity (%), and IC_{50} was performed using three technical replicates ($n=3$). The results demonstrated high precision, with coefficients of variation below 1%, confirming consistency. Data normality supported parametric analysis. A strong positive, although not statistically significant, correlation was observed between TPC and DPPH% ($r=0.866$, $p=0.333$).

3.3.1. Total Phenolic Content (TPC)

As shown in [Table3], (YROP) extract exhibited a high total phenolic content (TPC) of 37.36 ± 0.26 mg GAE/g DW, quantified via an optimized Folin–Ciocalteu method with excellent precision ($R^2=0.9986$; $CV < 1\%$). This TPC surpasses values reported in previous studies, such as 7.85–19.01 mg GAE/g DW in Greek red onion peels [40] and 5.34 mg GAE/g DW in Malaysian red onion bulbs [41], likely due to cultivar, environmental, and plant part differences. A moderate positive correlation ($r=0.866$) between TPC and DPPH scavenging activity (49.05%) suggested that phenolics substantially contribute to antioxidant capacity, in contrast to the weaker associations reported elsewhere. These results highlight the phytochemical richness and antioxidant potential of (YROP) extract, supporting its use as a natural antioxidant in food and pharmaceutical applications.

3.3.2. Antioxidant Activity (DPPH and IC_{50})

As presented in [Table3], the (YROP) extract exhibited moderate but meaningful antioxidant activity in the DPPH assay, with $49.05 \pm 0.44\%$ inhibition and an IC_{50} of 111.50 ± 0.00 μ g/mL, indicating effective free radical scavenging. The analysis demonstrated high precision with a coefficient of variation below 1%. The inverse correlation between DPPH inhibition and IC_{50} aligns with established antioxidant behavior [24]. The extract's high total phenolic content (37.36 mg GAE/g DW), particularly its quercetin content, underscores its role in enhancing antioxidant capacity through radical neutralization and modulation of antioxidant enzymes [42]. These findings highlight the potential of the extract as a natural antioxidant to improve the oxidative stability in various applications.

The red onion peel extract obtained via conventional extraction exhibited high analytical repeatability and moderate antioxidant activity, with notable phenolic content. These findings highlight its potential as a natural antioxidant for applications in food preservation and related industries.

4. CONCLUSION AND FUTURE WORK

4.1. CONCLUSION

This study highlights the potential of (YROP) extract as a natural antioxidant that enhances RBDPO Oil stability under heat stress. When tested at 200 and 400ppm during 25 h deep-frying at 170–180°C, the 400ppm extract reduced free fatty acid and peroxide values by over 20%, preserved red color intensity (11.77 Lovibond units), and increased the oxidative stability index (OSI) to 15.20h comparable to TBHQ (17.53h), and was superior to the control (10.25h). The effectiveness of the extract was confirmed by its significant DPPH scavenging activity (49.05%) and high total phenolic content (37.36 mg GAE/g DW). These findings endorse (YROP) extract

**Table[3]:** Phytochemical Characteristics of (YROP) Extract

Phytochemical Parameter	Mean \pm SD
Total Phenolic Content (TPC) (mg GAE/g DW)	37.36 \pm 0.26
DPPH Radical Scavenging Activity (%)	49.05 \pm 0.44
DPPH IC ₅₀ (μ g/mL)	111.50 \pm 0.00

Note: Values are expressed as mean \pm SD (n = 3). TPC = Total Phenolic Content; IC₅₀ = Concentration required to inhibit 50% of DPPH radicals; GAE = Gallic Acid Equivalents; DW = Dry Weight.

as a sustainable alternative to synthetic antioxidants, improving oil quality, shelf life, and adding value to agro-industrial waste

4.2. FUTURE WORK

While this study confirmed the effectiveness of (YROP) extract in enhancing RBDPO Oil stability, further research is recommended. Future work should evaluate its performance in other edible oils and conditions, assess its safety and sensory acceptance, and explore antioxidant mechanisms and formulation strategies to improve its thermal stability and practical use.

Note: This study is derived from the Ph.D. dissertation submitted to Sana'a University, Faculty of Agriculture, Food and Environment, Department of Food Science and Nutrition.

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