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Valorization of Pomegranate Peel Waste: Extraction of Phenolic-Rich Fractions and Their Antioxidant Performance

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Abstract— *Pomegranate (Punica granatum L.) peel, a byproduct of juice extraction, is rich in phenolics, flavonoids, and tannins. This study aimed to optimize the extraction of these bioactive compounds from pomegranate peel extract (PPE). It also evaluated PPE's efficacy in inhibiting lipid peroxidation in a high-unsaturated-lipid system. Total phenolic content (TPC) and DPPH scavenging activity (DPPH•-SA) were used as indicators of antioxidant potential. Extraction was optimized using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD) to assess the effects of temperature, time, and ethanol concentration. The optimal conditions were set at 65°C for 60 min using 70% ethanol, yielding a TPC = 231.8 mg GAE/g dry weight. The DPPH•-SA of PPE was 91.8%, with an IC_{50} = 16.92 µg/mL. The antioxidant performance of PPE was validated in refined, bleached, deionized sunflower oil (SFO) using the Rancimat assay. PPE at 250 µg/g extended the SFO induction period from 8.32 to 15.90 h. This resulted in a Relative Stability Index = 1.91 and a Free Radical Scavenging = 91.11%. These findings demonstrate that PPE's antioxidant activity is comparable to synthetic antioxidants like TBHQ and BHT. This makes it a sustainable alternative to synthetic antioxidants and a valuable option for food and healthcare applications.*

Keywords— Pomegranate peel extract, Agro-industrial waste, Valorization, Polyphenols, Response Surface Methodology (RSM), Sustainable food preservation.

I. INTRODUCTION

Pomegranate (*Punica granatum* L.) is widely cultivated in the Middle East, Africa, and Asia and is valued for its nutritional and functional properties (Filipovic et al., 2025; Mohlamonyane et al., 2024). During industrial processing, a substantial portion of the fruit, primarily the peel, is discarded as waste, accounting for up to 40% of the total fruit mass (Himel et al., 2024). This byproduct represents a significant and underutilized source of bioactive compounds.

Pomegranate peel is particularly rich in polyphenolic constituents, including ellagitannins (e.g., punicalagins), phenolic acids, and flavonoids (Liu et al., 2024; Vasisht et al., 2024). These compounds are recognized for their strong antioxidant properties, largely due to their ability to donate hydrogen atoms or electrons to reactive species (Andrade et al., 2024; Salim et al., 2023). As a result, pomegranate peel extract (PPE) has attracted increasing attention as a natural antioxidant that

inhibits lipid oxidation in food systems. The replacement of synthetic antioxidants with plant-derived alternatives has become a key objective in food preservation, driven by consumer demand for safer and more sustainable ingredients (Salim et al., 2023).

The recovery of phenolic compounds from plant matrices depends strongly on extraction conditions. Parameters such as solvent composition, temperature, and extraction time influence both extraction efficiency and the integrity of bioactive molecules (Liu et al., 2024; Rashed et al., 2018). Aqueous ethanol is commonly employed due to its suitable polarity for solubilizing a broad range of phenolic compounds (Nawaz et al., 2020). However, conventional extraction methods often suffer from limited mass transfer and prolonged processing times, thereby reducing overall efficiency.

To address these limitations, intensified extraction techniques have been developed. Among them, ultrasonic–microwave-assisted extraction (UMAE) combines the effects of acoustic cavitation and rapid internal heating, leading to enhanced disruption of plant cell structures and improved solvent penetration (Kaderides et al., 2021; Rashed et al., 2016). This dual mechanism accelerates the release of intracellular compounds and has been shown to improve the recovery of phenolic compounds compared with conventional approaches.

Despite the recognized potential of pomegranate peel as a source of natural antioxidants, the relationship between extraction conditions, phenolic recovery, and functional performance in lipid systems remains insufficiently clarified. In particular, linking extraction efficiency with practical antioxidant performance under oxidative conditions is essential for evaluating real-world applicability.

In this context, the present study investigates the extraction of phenolic-rich fractions from pomegranate peel using an intensified extraction approach. The antioxidant capacity of the obtained extract was evaluated using radical-scavenging assays and further validated in a lipid system through thermo-oxidative stability analysis. This work aims to demonstrate the potential of pomegranate peel as a sustainable source of natural antioxidants for food preservation applications.

II. MATERIALS AND METHODS

2.1 Sample Collection and Reagents:

Pomegranate (*Punica granatum* L.) fruits were collected from Suzhou, Anhui, China, in September 2024. The peels were manually separated, rinsed with tap water, and dried in a hot-air oven at 40 ± 2°C for 24 h. The dried material was ground and passed through a 60-mesh sieve to obtain a fine powder. Moisture content, determined at 105°C, was 8.4% (w/w). The powder was stored in sealed containers at room temperature and protected from light.

All chemicals and solvents were of analytical grade and obtained from commercial suppliers, including Sinopharm Chemical Reagent Co. (China), Macklin (Shanghai, China), TCI Europe N.V. (Belgium), and Sigma-Aldrich (USA).

2.2 Extraction Processes:

Polyphenols were extracted from PP using ultrasonic/microwave-assisted extraction (UMAE) and maceration-assisted extraction (MAC). UMAE was optimized by Response Surface Methodology (RSM) with a Box–Behnken design (BBD) to maximize recovery, while maceration extraction (MAC) served as a control. This comparison highlights UMAE advantages, including higher efficiency, reduced time and energy use, with temperature, time, and solvent concentration as key parameters.

2.3 Maceration Extraction:

Maceration extraction (MAC) was used as the conventional control (Zhang et al., 2024) with slight modifications. Ten grams of PP powder were mixed with 400 mL of 70:30 (v/v) ethanol–water and incubated at 60°C for 60 min in a thermostatic shaking water bath.

2.4 Ultrasonic/Microwave-Assisted Extraction:

UMAE was employed to enhance polyphenol recovery from PP, using combined ultrasonic and microwave energy (Rashed et al., 2016). Extraction was performed in a dual-mode reactor (200 W ultrasound, 150 W microwave), in which 10 g of PP was mixed with 300 mL of 70% ethanol–water at a 1:30 (w/v) ratio (Vargas-Torrico et al., 2024) and treated at 60 ± 1°C for 10 min. The extract was filtered, concentrated, diluted to 50 mL with distilled water, and stored at 4°C. The extract was vacuum-filtered, concentrated by rotary evaporation at 50°C, reconstituted to 50 mL with distilled water, and stored at −4°C for analysis.

2.5 Colorimetric Estimation of Polyphenols:

Total phenolic content (TPC) was determined using the Folin-Ciocalteu method according to Liu et al. (2024), with gallic acid (0–200 mg/L) for calibration. Results were expressed as mg gallic acid equivalents per gram of dry matter (mg GAE/g DM). All measurements were performed in triplicate and reported as mean ± standard deviation.

2.6 DPPH Radical Scavenging Assay:

Antioxidant capacity was evaluated using the DPPH radical scavenging assay (DPPH•-SA) following Rashed et al. (2022), where PPE (10–160 µg/mL) was mixed with 60 µM DPPH, incubated for 30 min in the dark, and measured at 517 nm; TBHQ and BHT were used as positive controls. IC_{50} values were obtained from inhibition versus log concentration plots, and all experiments were conducted in triplicate.

$$\text{DPPH} \bullet -\text{SA}\% = \frac{A_0 - A_1}{A_0} \times 100 \quad (1)$$

Where A_0 is the absorbance of the control (DPPH solution without sample), and A_1 is the absorbance of the sample (with PPE).

2.7 Experimental Design and Optimization:

Optimization was performed using RSM combined with Box–Behnken Design (BBD). Extraction parameters, including temperature (50–80°C), time (40–80 min), and ethanol concentration (60–80%), were optimized to maximize the yields of TPC and DPPH•-SA. Experimental design and statistical analysis were carried out using Design-Expert 13.0 (Stat-Ease Inc., USA). Experimental data were fitted to second-order polynomial (quadratic) models describing the relationship between extraction parameters and measured responses. The general form of the response surface model is expressed as Eq. (2):

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + + \sum_{i=1}^{3} \beta_{ii} \beta {X_i}^2 + \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{ij} X_i X_j \quad (2)$$

where: Y is the response (TPC or DPPH•-SA), β_0 is the intercept, β_i, β_{ii}, and β_{ij} represent linear, quadratic, and interaction effects, respectively. X_i and X_j are the coded independent variables.

Model adequacy was assessed using analysis of variance (ANOVA) to test the significance of regression coefficients ($p < 0.05$). Goodness-of-fit was evaluated through R^2, adjusted R^2, predicted R^2, and adequate precision. Finally, the RSM-predicted optimal extraction conditions were experimentally validated. The observed TPC and DPPH•-SA values under optimal conditions were compared with the predicted values. Experimental validation is crucial, as strong agreement between actual and predicted values confirms the model's accuracy and practical relevance.

2.8 Statistical Analysis:

All results are expressed as mean ± standard deviation (n = 3). A one-way ANOVA followed by Tukey's test revealed significant differences at $p < 0.05$. Statistical analyses were conducted using SPSS 25.0 (IBM, USA).

III. RESULTS AND DISCUSSION

3.1 Effect of the Extraction Process on the Yield:

The extraction yield of crude extract differed noticeably between the applied methods. Maceration resulted in a relatively lower yield of 12.8% (w/w), reflecting limited recovery under conventional diffusion-controlled conditions. The prolonged solvent contact enables gradual extraction; however, mass transfer remains limited, reducing overall efficiency. In contrast, ultrasonic–microwave-assisted extraction (UMAE) produced a higher extract yield of 18.5% (w/w). This increase can be attributed to enhanced mass transfer driven by the combined action of ultrasonic and microwave energy. Ultrasonic cavitation facilitates the release of intracellular constituents, while microwave irradiation accelerates solvent penetration through rapid internal heating. The combined effects improve solvent accessibility to the plant matrix and promote more efficient transfer of solutes into the extraction medium. As a result, UMAE provides a higher recovery of crude extract in a shorter processing time than maceration. These numbers are consistent with other studies on PP extraction (Rashed et al., 2016; Vargas-Torrico et al., 2024).

3.2 Total Phenolic Content:

SEM results support the TPC findings, with UMAE causing more severe cell wall disruption than maceration, enhancing solvent penetration and phenolic diffusion. UMAE produced a significantly higher TPC = 225.6 mg GAE/g DW ($p < 0.05$), compared to 196.5 mg GAE/g DW for maceration (Fig. 1a). This confirms UMAE's superior extraction efficiency. Similar results were found by Sweidan et al. (2023), with a maximum TPC = 297.70 ± 1.73 mg GAE/g DW in ethanol-based extracts. The differences in results can be attributed to variations in solvent concentration, particle size, and extraction energy input. Ethanol's polarity enhances solute-solvent interactions, improving phenolic extraction efficiency (Marchi et al., 2015; Rashed et al., 2016).

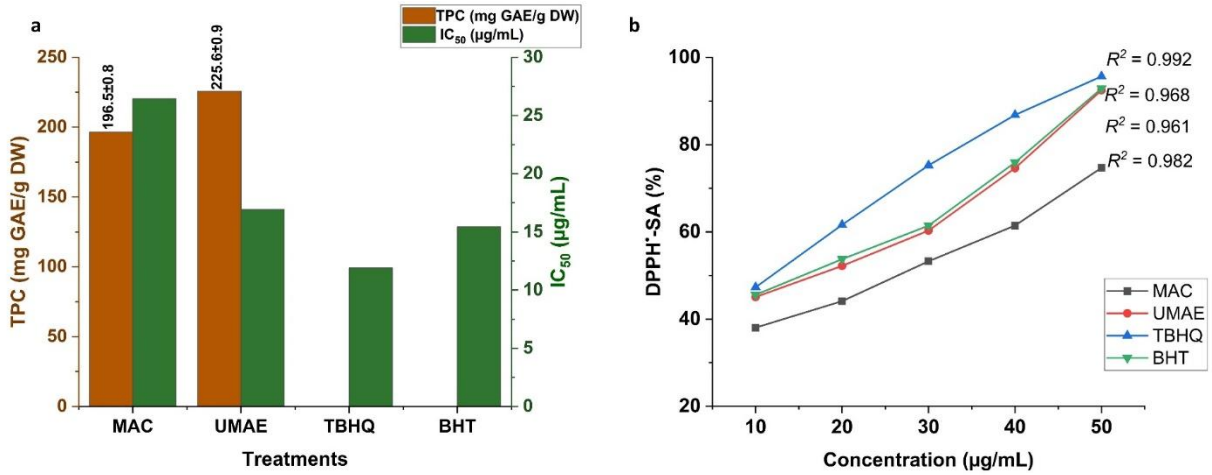

FIGURE 1. (a) Total phenolic content (TPC) and DPPH scavenging (DPPH•-SA) in terms of IC_{50} (µg/mL), and (b) DPPH•-SA (%) of maceration extraction (MAC), ultrasonic/microwave-assisted extraction (UMAE), TBHQ, and BHT.

3.3 DPPH• Scavenging:

UMAE demonstrated the highest antioxidant activity, with an IC_{50} of 16.92 µg/mL (Fig. 1b). At 50 µg/mL, UMAE achieved 92.46% inhibition, outperforming maceration (IC_{50} of 26.45 µg/mL; 74.70% inhibition). UMAE and BHT showed similar IC_{50} values ($p > 0.05$), indicating comparable radical-scavenging potency. BHT had an IC_{50} = 15.43 µg/mL and 92.86% inhibition. TBHQ showed the highest activity (IC_{50} = 11.89 µg/mL, 96.66% inhibition), significantly outperforming all other treatments ($p < 0.05$). These results align with previous studies indicating TBHQ's superior antioxidant activity (Bi et al., 2025; Shanlee et al., 2025). The concentration-dependent increase in DPPH• inhibition (10–50 µg/mL) confirms a dose-response relationship (Pfleger et al., 2025; Sweidan et al., 2023). The strong antioxidant activity of UMAE suggests PPE as a viable natural alternative to BHT. This is crucial in stabilizing high-fat food products. Phenolics in PPE are key contributors to antioxidant activity, neutralizing free radicals and reducing oxidative stress (More & Arya, 2024). TPC is a reliable indicator of antioxidant activity, with higher values often linked to stronger antioxidant activity (Khan et al., 2025). DPPH• results further confirm polyphenols' role in neutralizing free radicals and chelating transition metals (Yu et al., 2025).

3.4 Optimization Results:

RSM combined with BBD was used to optimize extraction parameters. This approach evaluates multiple factors simultaneously, providing more efficient optimization than single-variable methods (Giri et al., 2023). Significant interactions among extraction temperature, time, and ethanol concentration were identified, optimizing both TPC and DPPH•-SA.

3.5 Statistical Interpretation and Model Predictions:

RSM showed that extraction temperature had the greatest effect on TPC and DPPH•-SA, followed by time and ethanol concentration. Diagnostic analyses, including residual behavior and predictive reliability, are provided in Fig. 2. These results confirm RSM's efficiency for multi-factor optimization, as shown by previous studies (Giri et al., 2023; Kim & Yoon, 2023). The regression equations for TPC and DPPH•-SA are provided below:

$$Y_1 = 230.36 - 11.86A - 1.02B - 0.1625C - 2.08AB + 0.5500AC + 0.8250BC - 18.56A^2 - 3.23B^2 - 9.45C^2 \quad (3)$$

$$Y_2 = 91.60 – 2.80A – 0.0500B + 0.1500C – 0.0250AB + 0.2750AC + 0.6250BC – 5.69A^2 - 1.19B^2 - 3.64C^2 \quad (4)$$

where: Y_1 and Y_2 refer to the TPC (mg GAE/g DW) response and DPPH•-SA (%) response, respectively; A refers to extraction temperature (°C); B refers to extraction time (min); and C refers to ethanol concentration (%). These equations describe the relationship between factors and responses, confirming the model's excellent performance.

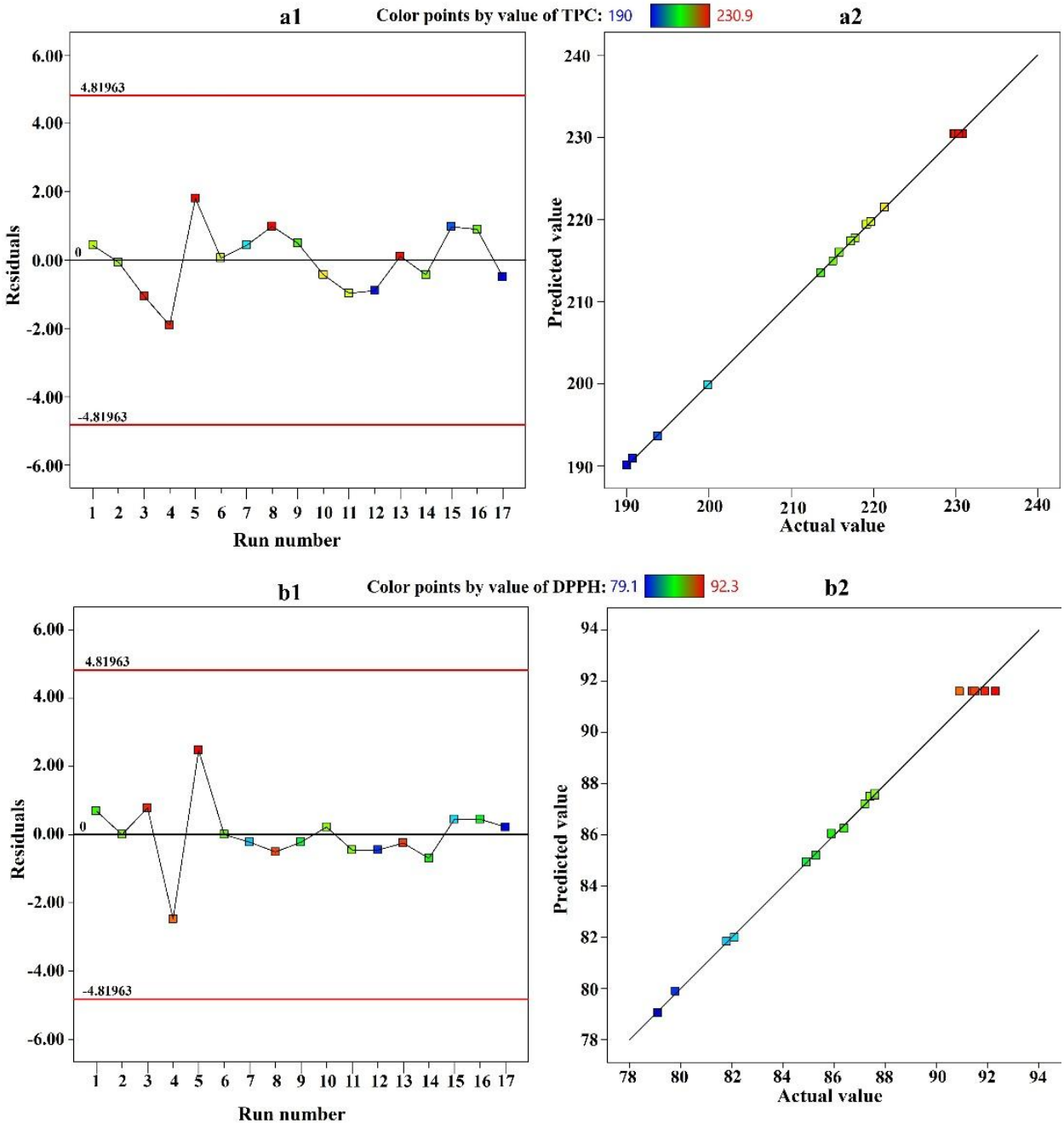

FIGURE 2: Diagnostic evaluation plots for RSM models based on BBD: correlations between residuals and runs (a1, b1), and between predicted and actual values (a2, b2) for TPC and DPPH•-SA%, respectively.

Table 1 presents the BBD matrix with the actual and coded levels of extraction parameters. Runs 3-5, 8, and 13 recorded the highest actual values for both TPC (229.8 – 230.9 mg GAE/g DW) and DPPH•-SA% (90.9 – 92.3%). Among these, Run 5 achieved the highest TPC (231.8 mg GAE/g DW) and DPPH•-SA (92.3%) under optimal conditions of 65°C for 60 min in 70% ethanol. The predicted and actual values are closely aligned, confirming the model's accuracy. The residual and average Absolute Percent Error (APE) for TPC were 0.5 and 0.22%, respectively. For DPPH•-SA, these values were -0.2 and 0.22%, demonstrating excellent model predictability and reliability. These small deviations (< 0.5%) validate the robustness and predictive capability of the quadratic models derived using RSM with BBD, ensuring minimal experimental deviation.

TABLE 1

BOX–BEHNKEN DESIGN (BBD) MATRIX WITH ACTUAL FACTOR LEVELS, ACTUAL AND PREDICTED RESPONSES, RESIDUALS, AND ABSOLUTE PERCENT ERRORS (APE%) FOR TPC (Y_1) AND DPPH•-SA (Y_2) OF POMEGRANATE PEEL EXTRACT (PPE)

Run	A: Temperature (°C)	B: Time (min)	C: Ethanol (%)	TPC Actual (mg GAE/g DW)	TPC Predicted (mg GAE/g DW)	Residual	APE%	DPPH•-SA Actual (%)	DPPH•-SA Predicted (%)	Residual	APE%
1	65	40	80	217.8	217.7	0.1	0.05	86.4	86.3	0.1	0.12
2	65	80	80	217.3	217.3	0	0	87.6	87.6	0	0
3	65	60	70	230	230.4	-0.4	0.17	91.9	91.6	0.7	0.76
4	65	60	70	229.8	230.4	-0.6	0.26	90.9	91.6	-0.7	0.77
5	65	60	70	230.9	230.4	0.5	0.22	92.3	91.6	-0.2	0.22
6	65	40	60	219.7	219.7	0	0	87.2	87.2	0	0
7	80	40	70	199.9	199.8	0.1	0.05	81.8	81.9	-0.1	0.12
8	65	60	70	230.7	230.4	0.3	0.13	91.4	91.6	0.2	0.22
9	50	60	80	213.6	213.5	0.1	0.05	84.9	85	-0.1	0.12
10	50	80	70	221.4	221.5	-0.1	0.05	87.6	87.6	0	0
11	50	40	70	219.2	219.4	-0.2	0.09	87.4	87.5	-0.1	0.11
12	80	60	80	190.7	190.9	-0.2	0.1	79.8	79.9	-0.1	0.13
13	65	60	70	230.4	230.4	0	0	91.5	91.6	-0.1	0.11
14	65	80	60	215.9	216	-0.1	0.05	85.9	86.1	-0.2	0.23
15	80	80	70	193.8	193.6	0.2	0.1	82.1	82	0.1	0.12
16	50	60	60	215.1	214.9	0.2	0.09	85.3	85.2	0.1	0.12
17	80	60	60	190	190.1	-0.1	0.05	79.1	79.1	0	0

Center points: Runs 3-5, 8, and 13. Residual = Actual value – Predicted value; APE = |Residual/Actual value| × 100. Average APE: TPC = 0.10%; DPPH•-SA = 0.17%.*

3.6 Model Significance and Analysis of Variance:

ANOVA results for the quadratic models of TPC (Y_1) and DPPH•-SA (Y_2) are summarized in Tables 2 and 3. Both models were significant ($p < 0.0001$), with non-significant lack-of-fit values ($p > 0.05$) confirming the models' predictive reliability. For both models, lack-of-fit p-values were 0.8344 (TPC) and 0.9479 (DPPH•-SA). This confirms that the quadratic models represent the relationships between extraction parameters and responses. Significant terms (temperature, time, and ethanol level) accounted for the variance in both responses.

For TPC, the model showed an $R^2 = 0.9997$, adjusted $R^2 = 0.9993$, and predicted $R^2 = 0.9987$. These values indicate a near-perfect correlation between actual and predicted values, confirming the model's accuracy. Adeq Precision (136.55) and a low coefficient of variation (0.18%) demonstrate excellent model precision. Temperature (A) had the greatest linear effect ($p < 0.0001$), followed by the quadratic terms A^2, B^2, and C^2. These findings confirm strong curvature, indicating non-linear interactions in the design space.

For DPPH•-SA, the quadratic model achieved $R^2 = 0.9957$. The adjusted $R^2 = 0.9901$ and the predicted $R^2 = 0.9883$ indicate a reliable fit to the data. The model showed Adeq Precision (39.28) and coefficient of variation (0.48%). Extraction temperature (A) had the greatest influence ($p < 0.0001$), followed by significant quadratic terms (A^2, B^2, C^2). The BC interaction was significant ($p = 0.0199$), indicating a synergistic effect between extraction time and ethanol concentration. These findings confirm that temperature is the primary factor influencing both TPC and DPPH•-SA, with extraction time and ethanol concentration also modulating their efficiency. High determination coefficients and strong precision indices validate the robustness of RSM models, with lack-of-fit confirming predictive accuracy.

TABLE 2

ANALYSIS OF VARIANCE (ANOVA) FOR THE QUADRATIC MODEL FOR POMEGRANATE PEEL EXTRACT'S TOTAL PHENOLIC CONTENTS (mg GAE/g DW)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Note
Model	3161.63	9	351.29	2377.04	< 0.0001	significant
A (Temperature)	1125.75	1	1125.75	7617.46	< 0.0001	
B (Time)	8.4	1	8.4	56.87	0.0001	
C (Ethanol)	0.2112	1	0.2112	1.43	0.2708	
AB	17.22	1	17.22	116.54	< 0.0001	
AC	1.21	1	1.21	8.19	0.0243	
BC	2.72	1	2.72	18.42	0.0036	
A^2	1449.63	1	1449.63	9809.03	< 0.0001	
B^2	43.93	1	43.93	297.24	< 0.0001	
C^2	376.41	1	376.41	2546.99	< 0.0001	
Residual	1.03	7	0.1478			
Lack of Fit	0.1825	3	0.0608	0.2856	0.8344	not significant
Pure Error	0.852	4	0.213			
Cor Total	3162.66	16				

Standard deviation = 0.3844; Mean = 215.66; C.V. % = 0.1783; R^2 = 0.9997; Adjusted R^2 = 0.9993; Predicted R^2 = 0.9987; Adeq Precision = 136.5469*

TABLE 3

ANALYSIS OF VARIANCE (ANOVA) FOR THE QUADRATIC MODEL FOR THE DPPH•-SA (%) OF POMEGRANATE PEEL EXTRACT

Source	Sum of Squares	df	Mean Square	F-value	p-value	Note
Model	278.75	9	30.97	178.44	< 0.0001	significant
A (Temperature)	62.72	1	62.72	361.35	< 0.0001	
B (Time)	0.02	1	0.02	0.1152	0.7442	
C (Ethanol)	0.18	1	0.18	1.04	0.3424	
AB	0.0025	1	0.0025	0.0144	0.9078	
AC	0.3025	1	0.3025	1.74	0.2283	
BC	1.56	1	1.56	9	0.0199	
A^2	136.2	1	136.2	784.7	< 0.0001	
B^2	5.94	1	5.94	34.21	0.0006	
C^2	55.71	1	55.71	320.97	< 0.0001	
Residual	1.21	7	0.1736			
Lack of Fit	0.095	3	0.0317	0.1131	0.9479	not significant
Pure Error	1.12	4	0.28			
Cor Total	279.96	16				

Standard deviation = 0.4166; Mean = 86.65; C.V. % = 0.4808; R^2 = 0.9957; Adjusted R^2 = 0.9901; Predicted R^2 = 0.9883; Adeq Precision = 39.2762*

3.7 Response Surface Analysis:

Three-dimensional (Fig. 3a-c, Fig. 4a-c) and contour plots (Fig. 3d-f, Fig. 4d-f) revealed the optimal conditions for the highest TPC and DPPH•-SA. The highest TPC (230.9 mg GAE/g DW) and DPPH•-SA (92.3%) were obtained at 65°C for 60 min using 70% ethanol. The predicted maximum response for TPC was 230.4 mg GAE/g DW. For DPPH•-SA, it was 91.9%. Lower extraction conditions, e.g., 50°C, 40% ethanol, and 40 min, resulted in the lowest values. Intermediate conditions produced moderate TPC and DPPH•-SA values, indicating a balanced extraction. Ethanol concentration significantly influenced extraction efficiency, with 70% ethanol yielding the highest TPC and antioxidant activity.

The surface and contour plots of TPC (Fig. 3a-f) and DPPH•-SA (Fig. 4a-f) confirm optimal extraction conditions. They also demonstrate significant interactions among variables. Each plot clearly reflects the curvature of the response surface predicted by the quadratic model. Response surface plots indicate that extraction temperature and time were the primary factors influencing TPC and DPPH•-SA.

However, temperatures > 70°C resulted in a slight decrease in TPC, likely due to thermal degradation of phenolics. Ethanol (70%) yielded the highest TPC, suggesting it is the optimal solvent polarity for solubilizing both hydrophilic and lipophilic phenolics. DPPH•-SA increased with temperature and time up to approximately 65°C and 60 min, then it declined at higher temperatures and times. The optimal ethanol concentration, similar to TPC, was near 70%. Moderate ethanol levels improved antioxidant activity, whereas excessively high concentrations reduced extraction efficiency. The close alignment between the graphical trends and ANOVA outcomes demonstrates that the model reliably captured the experimental behavior. The response surfaces also provide valuable insights for optimizing the process and scaling up under controlled thermal conditions.

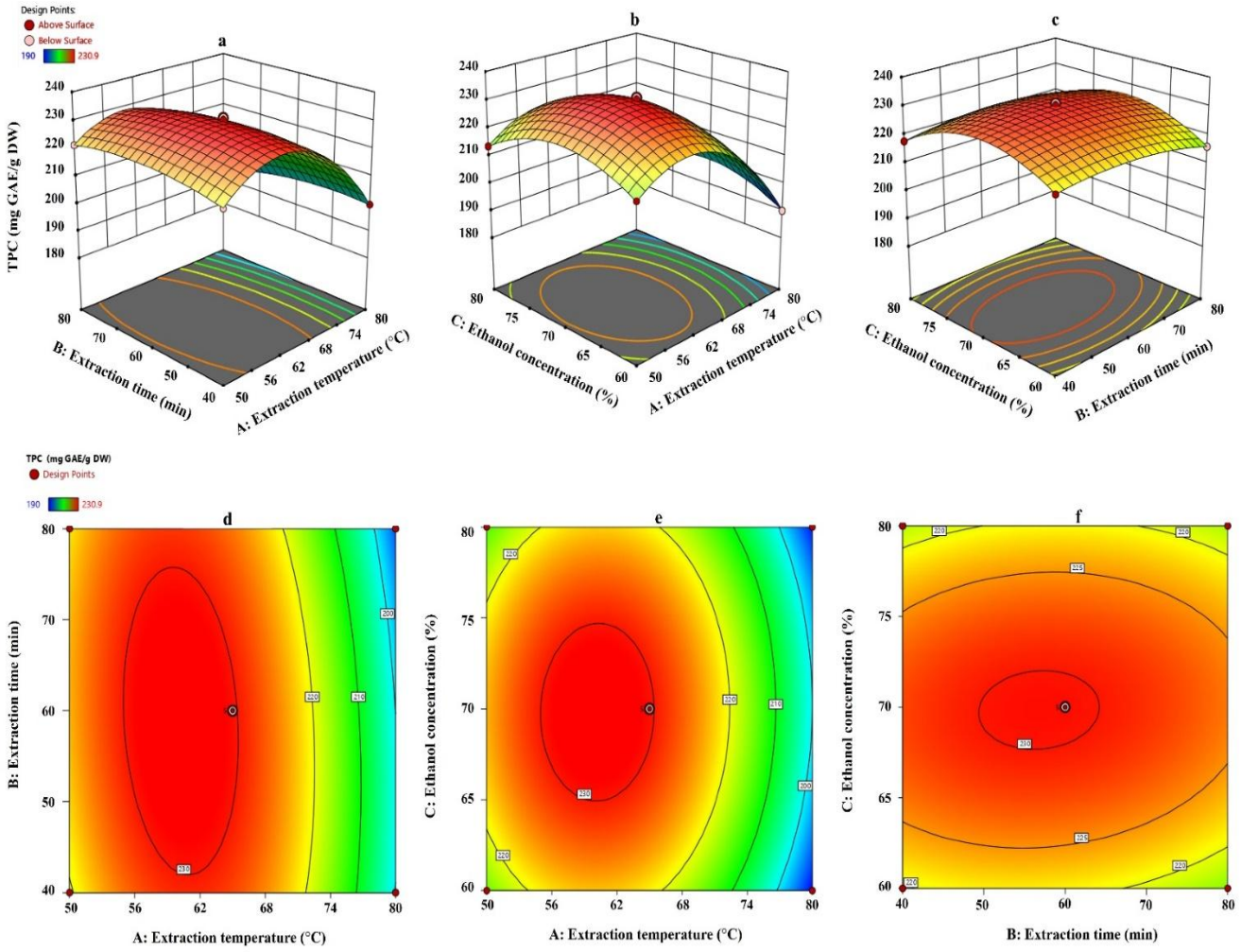

FIGURE 3: The 3D surface plot based on Box-Behnken Design experiment with total phenolic content (mg GAE/g DW) as the response (Y_1).

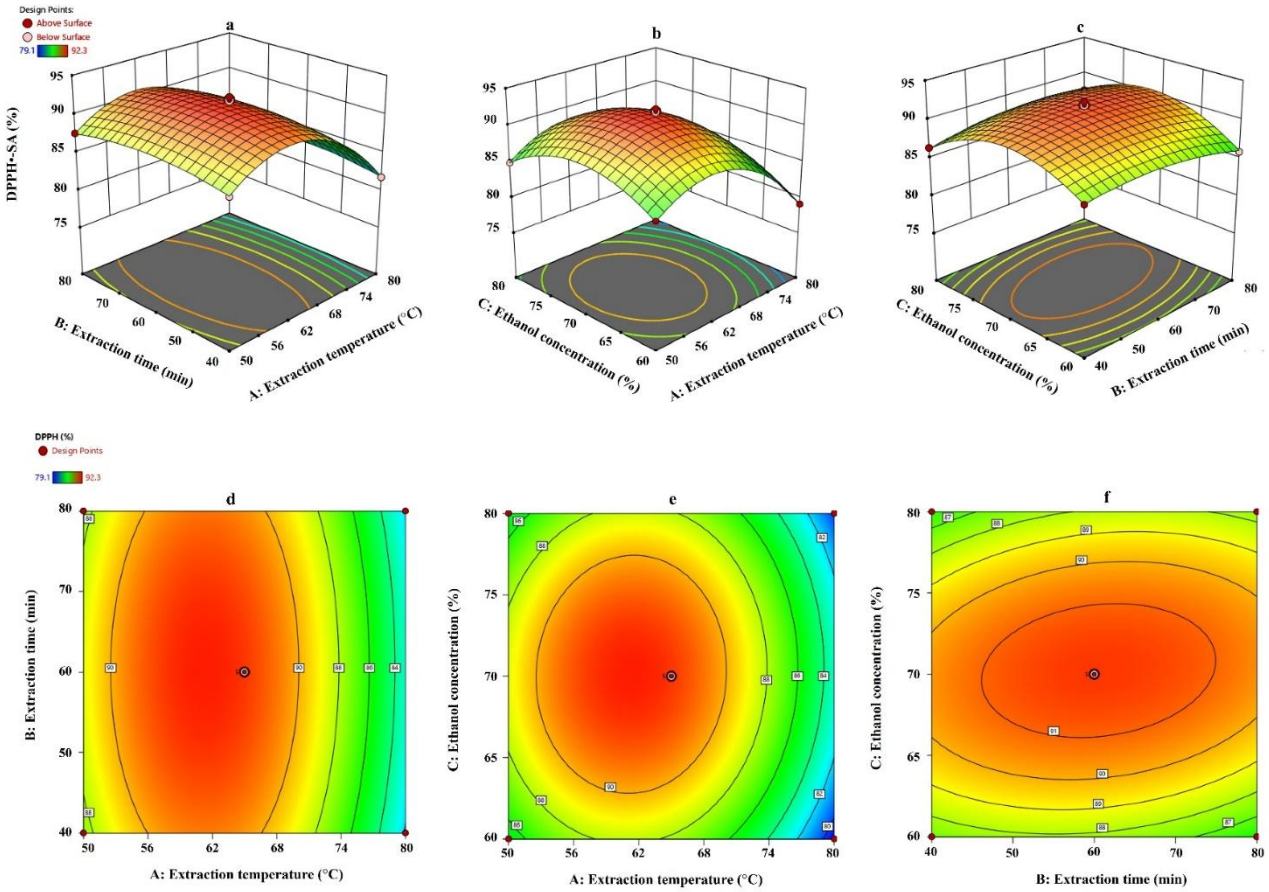

FIGURE 4: The 3D surface plot based on Box-Behnken Design experiment with DPPH•-SA (%) as the response (Y_2).

3.8 Verification of Optimized Conditions:

The optimized extraction conditions predicted by the RSM model were 65°C, 60 min, and 70% ethanol. Under these conditions, the experimental results closely matched the actual and predicted responses, confirming the model's reliability and predictive accuracy. The verified TPC value was 231.8 mg GAE/g DW, closely matching the model values of actual (230.9 mg GAE/g DW) and predicted (230.4 mg GAE/g DW). Similarly, the verified DPPH•-SA% was 91.8%, while the actual and predicted values were 92.3% and 91.6%, respectively. These results further confirm the reproducibility of the experiment. The narrow standard deviations observed across replicates indicate consistent performance and minimal experimental error within the optimized design space. These findings confirm that the model accurately captures the interaction effects among temperature, time, and solvent concentration. The validated conditions provide an effective framework for maximizing phenolic recovery and antioxidant activity from PPE. Furthermore, the optimized parameters can be applied to future scale-up studies or pilot-scale biorefinery processes for sustainable valorization of PPE.

IV. CONCLUSION

This study demonstrates the significant antioxidant activity of polyphenol extraction from pomegranate peel, thereby enhancing the oxidative stability of sunflower oil (SFO). Using RSM and BBD, optimal extraction conditions were identified: 65°C for 60 min with 70% ethanol. These conditions resulted in PPE with a high TPC = 231.8 mg GAE/g DW and potent antioxidant activity as demonstrated by a 91.8% inhibition in the DPPH•-SA assay. PPE's antioxidant activity was comparable to synthetic antioxidants such as TBHQ and BHT, demonstrating its potential as a sustainable, effective natural alternative. Additionally, the inclusion of PPE in SFO significantly extended its shelf life, highlighting its practical application as a natural antioxidant. However, concentrations > 250 µg/g may induce mild pro-oxidant effects, suggesting a concentration-dependent efficacy. These findings underscore the value of PPE as an eco-friendly and efficient source of antioxidants, offering a promising alternative to synthetic preservatives in the food industry. The use of PPE could enhance food safety and preservation while supporting the growing demand for natural ingredients.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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