

Green Valorization of Passion Fruit Peel via Microwave-Assisted Extraction: Optimization of Phenolic Recovery and Process Efficiency

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Abstract: Passion fruit (*Passiflora edulis f. flavicarpa* O. Deg.) peel is a sustainable phenolic source with potential for use as nutraceuticals and functional foods. This study optimized microwave-assisted extraction (MAE) via response surface methodology. A central composite design was used to evaluate the effects of the ethanol concentration (54.89–80.11%), microwave power (364.78–785.22 W), and irradiation time (1.64–8.36 min) on the total phenolic content (TPC). The optimized conditions—67% ethanol, 700 W, and 5.8 min—yielded 12.52 ± 0.27 mg gallic acid equivalents (GAE)/g dry basis, which was ~60% higher than that of conventional reflux extraction (7.80 ± 0.20 mg GAE/g) and nearly triple that of hot water extraction (4.50 ± 0.30 mg GAE/g). This work highlights MAE as a rapid, scalable, and environmentally sustainable strategy for valorizing agro-industrial byproducts. These findings provide a platform for future compound-level profiling, antioxidant activity validation, and pilot-scale processing to support the circular economy and nutraceutical innovation.

Keywords: *Passiflora edulis f. flavicarpa*, Microwave-assisted extraction, Phenolic compounds, Optimization, Response surface methodology

INTRODUCTION

The demand for sustainable recovery of plant bioactive compounds has intensified research on the valorization of agro-industrial byproducts for nutraceuticals, functional foods, and natural health products (1, 2). Phenolics are of particular interest because of their antioxidant, anti-inflammatory, cardioprotective, and anticancer properties, which are strongly associated with reduced chronic disease risk (2). Passion fruit (*Passiflora edulis f. flavicarpa* O. Deg.), cultivated extensively in tropical and subtropical regions, is valued for its pulp and juice, yet its peel—which represents nearly 50% of fruit mass—is routinely discarded as waste.

This peel contains abundant phenolic acids (e.g., caffeic, ferulic) and flavonoids (e.g., quercetin, luteolin), which are compounds with high antioxidant potential (3). The loss of these bioactive compounds not only represents economic inefficiency but also contributes to unnecessary agro-industrial waste streams. Valorizing passion fruit peel can therefore contribute to both public health benefits and circular economy initiatives.

Extraction method selection is critical because phenolic yield and stability are highly dependent

on solvent polarity, energy input, and temperature exposure. Conventional approaches, such as maceration and reflux extraction, are simple but have major drawbacks: maceration often requires days to weeks, excessive solvent consumption, and prolonged heat exposure, leading to degradation of thermolabile compounds (4). These inefficiencies reduce both extraction yield and sustainability. Green technologies such as microwave-assisted extraction (MAE) overcome these limitations by applying dielectric heating to rapidly disrupt plant cell walls and accelerate solvent diffusion. Compared with conventional methods, MAE reduces solvent use, shortens extraction to minutes, and minimizes the thermal degradation of phenolics (5). Recent innovations have integrated MAEs with computational optimization tools, such as response surface methodology (RSM) and machine learning, to precisely model and predict optimal extraction conditions. For example, Mobasheri et al. (6) applied machine learning to pomegranate peel and reported that microwave power was the dominant factor influencing phenolic recovery ($R^2 = 0.9998$). Similarly, hybrid RSM-ANN modeling for cactus cladodes (*Opuntia ficus-indica*) achieved >90% recovery efficiency, confirming the robustness of predictive tools for complex plant matrices (2).

Similarly, enzyme-assisted MAE has also shown promise: cellulase treatment combined with microwaves enhances phenolic release from pomegranate peel while eliminating unwanted byproducts such as 5-hydroxymethylfurfural, a thermal degradation marker (3). Despite such advances, comprehensive optimization of the MAE for passion fruit peel remains scarce. Current studies provide only proof-of-concept, without systematic evaluation of key process parameters—ethanol concentration, microwave power, and irradiation time—through statistical modeling. Addressing these gaps is vital for solidifying MAE as a reliable, sustainable technology for passion fruit byproduct valorization.

Therefore, this study was designed to (1) optimize MAE parameters for phenolic recovery from passion fruit peel using RSM; (2) evaluate model adequacy and validate predictions under

optimal conditions; and (3) benchmark MAE against reflux and hot-water extractions. By addressing these objectives, this work establishes a scalable and environmentally sustainable extraction strategy for transforming passion fruit peel into a phenolic-rich ingredient for nutraceuticals, functional foods, and cosmetics.

MATERIALS AND METHODS

Preparation of Plant Material

Fresh yellow passion fruits were sourced from certified orchards in Warin Chamrap District, Ubon Ratchathani Province, Thailand, during the 2024 harvest season (December–January). Fruits were selected for uniform ripening, characterized by a bright yellow pericarp, an intact exocarp, and the absence of visible microbial decay. To minimize biological variability, only fruits weighing 80–100 g with total soluble solids of 13–15 °Brix were included. The peel, representing ~50% of the fruit weight, was manually separated from the pulp and seeds with stainless-steel knives. Slices (~5 × 5 mm) were dried in a hot-air oven (Memmert GmbH+Co. KG, Schwabach, Germany) at 50 °C for 72 h until a constant weight was achieved. This temperature was chosen to balance enzyme inactivation and preservation of heat-sensitive compounds, which is consistent with optimized protocols for fruit byproducts (7).

The dried material was milled into a fine powder via a laboratory grinder (IKA A11 Basic Analytical Mill, IKA®-Werke GmbH & Co. KG, Staufen, Germany). The powder was sieved to a uniform particle size of <425 µm (40 mesh), enhancing the surface area and solvent penetration. The moisture content of the final powder was $7.2 \pm 0.4\%$ (w/w), which was determined gravimetrically by oven-drying 2 g of sample at 105 °C until a constant weight was reached. The powder was vacuum-packed in polyethylene bags and stored at -20 °C until analysis. A voucher specimen (UBU-PF001) was authenticated by a university botanist and deposited in the Faculty of Pharmaceutical Sciences herbarium.

Chemicals and Reagents

All chemicals and solvents were of analytical grade unless otherwise specified. Ethanol ($\geq 99.5\%$, absolute), Folin-Ciocalteu's reagent, sodium carbonate, and gallic acid were purchased from Sigma-Aldrich (St. Louis, MO, USA). Deionized water was prepared via a Milli-Q purification system (Merck Millipore, Burlington, MA, USA) and used throughout the study. Stock solutions of gallic acid (1 mg/mL) were freshly prepared for calibration curves. Folin-Ciocalteu's reagent was diluted tenfold with distilled water prior to use.

Microwave-Assisted Extraction

MAE was performed with a programmable microwave system (UBU01 microwave extraction system, Ubon Ratchathani University, Thailand) operating at a frequency of 2,450 MHz. Figure 1 illustrates the in-house microwave extraction system (UBU01), including the magnetron source, condenser, and safety module. The system was equipped with a temperature and pressure monitoring module to ensure reproducible extraction conditions. For each extraction run, 2.0 g

of dried peel powder was placed in a 250 mL round-bottom flask and mixed with 60 mL of hydroethanolic solvent (the ethanol concentration varied between 50–80% v/v according to the experimental design). A fixed solid-to-solvent ratio of 1:30 (g/mL) was selected on the basis of preliminary trials showing maximal phenolic recovery without excessive solvent use. At the industrial scale, this ratio can be reduced through solvent recycling and concentration steps to maintain feasibility. The microwave power was adjusted between 400–800 W, and the irradiation time ranged from 2–8 min depending on the design matrix. A magnetic stir bar was placed inside each flask to ensure uniform mixing during extraction. The flask was connected to a reflux condenser to prevent solvent loss by evaporation. Immediately after extraction, the mixtures were cooled to room temperature, filtered through Whatman No. 1 filter paper, and centrifuged at 4,000 rpm for 10 min to remove fine particles. The supernatants were collected and stored at $-20\text{ }^{\circ}\text{C}$ until further analysis. This method was selected because of its proven ability to increase phenolic recovery within minutes, with lower solvent use than conventional methods do (5, 8, 9).

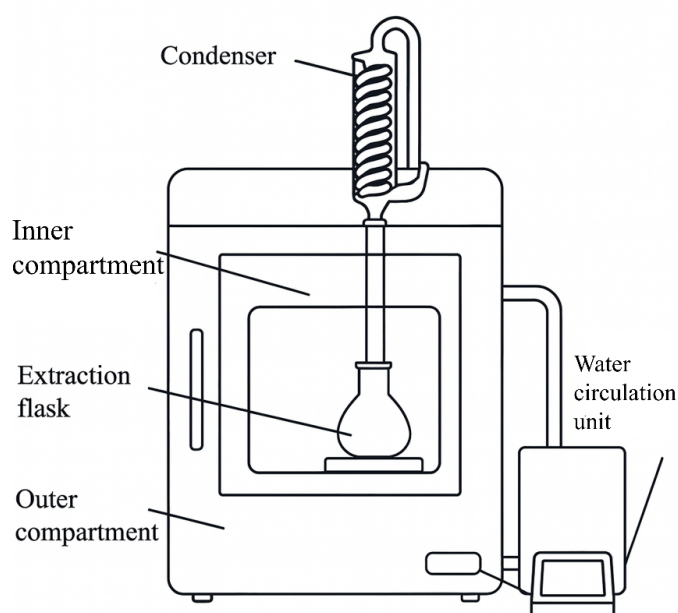


Figure 1. Schematic diagram of the in-house microwave-assisted extraction (MAE) system.

Conventional Extractions

Reflux Extraction

For comparison, reflux extraction was conducted using 2.0 g of dried peel powder and 60 mL of 65% ethanol in a round-bottom flask. The mixture was heated at 100 °C for 4 h under continuous stirring. After cooling, the extract was filtered, centrifuged, and stored under the same conditions as the MAE extracts.

Hot Water Extraction

Hot water extraction was also performed to simulate traditional methods. The procedure was identical to that of reflux, except distilled water was used to replace ethanol as the solvent. The extracts were filtered, centrifuged, and stored at -20 °C before analysis. These conditions represent traditional approaches widely reported in fruit phenolic extraction (10).

Experimental Design and Optimization

A central composite design (CCD) with three independent variables—ethanol concentration (X_1 , 50–80% v/v), microwave power (X_2 , 400–800 W), and irradiation time (X_3 , 2–8 min)—was used to evaluate their effects on total phenolic content (TPC). These factors and ranges were chosen on the basis of preliminary trials and prior literature, which identified solvent polarity, energy input, and extraction duration as the most influential variables for phenolic recovery. The design consisted of 20 experimental runs, including eight factorial points, six axial points, and six replicates at the center point, to estimate the pure error. The experimental matrix was randomized to minimize systematic bias. The response variable (Y) was defined as the TPC (mg gallic acid equivalents per gram dry basis, mg GAE/g dry basis). A quadratic polynomial regression model was fitted to the data:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j$$

where β_0 is the intercept, β_i represents the linear coefficient, β_{ii} represents the quadratic coefficient, and β_{ij} represents the interaction coefficient. Model

adequacy was assessed via ANOVA, coefficient of determination (R^2), adjusted R^2 , predicted R^2 , and lack-of-fit tests. Optimization was performed via the desirability function approach, which sought to maximize the TPC within the defined factor ranges. Statistica software version 12 (StatSoft, Inc., Tulsa, OK, USA) was used for data analysis.

Determination of Phenolic Content

The total phenolic content was determined via the Folin–Ciocalteu colorimetric method with slight modifications. Briefly, 0.5 mL of extract was mixed with 2.5 mL of tenfold-diluted Folin–Ciocalteu's reagent. After 5 min of incubation, 2.0 mL of 7.5% (w/v) sodium carbonate solution was added. The mixture was vortexed and incubated at room temperature in the dark for 30 min. Absorbance was measured at 725 nm via a UV–Vis spectrophotometer (Shimadzu UV-2101PC, Shimadzu Corporation, Kyoto, Japan). The calibration curve was expressed as $y = 0.0092x + 0.015$ ($R^2 = 0.999$). The results are expressed as mg gallic acid equivalents per gram dry basis (mg GAE/g dry basis). All the measurements were performed in triplicate, and the values are expressed as the means $\pm$ standard deviations (SDs).

Statistical Analysis

All the experiments were conducted in triplicate, and the data are expressed as the means $\pm$ SDs. One-way analysis of variance (ANOVA) was used to assess the significance of the model terms, with $p < 0.05$ considered statistically significant. Post hoc comparisons were carried out with Tukey's test when necessary. Residual analysis was conducted to confirm the model assumptions of normality and homoscedasticity. Diagnostic plots, including normal probability plots of residuals and predicted vs. observed values, were examined to ensure the adequacy of the regression model. The optimization process employs a desirability function that assigns equal weights to all factors and maximizes the TPC as the primary response. Validation experiments were conducted under the predicted optimal conditions to confirm the reliability of the model.

Table 1. Central composite design (CCD) matrix and observed response (TPC) for microwave-assisted extraction of phenolics from passion fruit peel

Run	Ethanol concentration (% v/v)	Microwave power (W)	Irradiation time (min)	TPC (mg GAE/g dry basis)
1	60.00	700.00	7.00	11.69 ± 0.11 ^{ab}
2	80.11	575.00	5.00	8.53 ± 0.15 ^d
3	75.00	700.00	3.00	10.61 ± 0.18 ^{bc}
4	75.00	700.00	7.00	11.30 ± 0.20 ^{ab}
5	60.00	450.00	3.00	8.68 ± 0.14 ^d
6	67.50	575.00	5.00	11.47 ± 0.27 ^{ab}
7	67.50	575.00	5.00	11.33 ± 0.22 ^{ab}
8	67.50	575.00	5.00	11.89 ± 0.19 ^a
9	67.50	364.78	5.00	9.33 ± 0.21 ^{cd}
10	67.50	575.00	5.00	11.52 ± 0.17 ^{ab}
11	60.00	450.00	7.00	9.57 ± 0.24 ^{cd}
12	67.50	575.0	1.64	9.71 ± 0.16 ^{cd}
13	67.50	575.0	5.0	11.96 ± 0.18 ^a
14	67.50	785.22	5.00	12.98 ± 0.20 ^a
15	75.00	450.00	7.00	9.24 ± 0.28 ^{cd}
16	54.89	575.00	5.00	9.09 ± 0.21 ^{cd}
17	60.00	700.00	3.00	10.95 ± 0.25 ^{bc}
18	75.00	450.00	3.00	8.39 ± 0.23 ^d
19	67.50	575.00	8.36	11.04 ± 0.26 ^{ab}
20	67.50	575.00	5.00	11.81 ± 0.22 ^a

Different superscript letters indicate significant differences between groups at $p < 0.05$. The data are expressed as the means ± SDs, $n = 3$.

Ethical and Safety Considerations

Although the study did not involve human or animal subjects, laboratory procedures were performed under institutional biosafety guidelines. All solvents and chemicals were handled via appropriate protective equipment, and waste was disposed of according to the hazardous waste management protocols of Ubon Ratchathani University.

RESULTS

Experimental Design and Model Fitting

The CCD generated 20 runs covering various ethanol concentrations (50–80%), microwave powers (400–800 W), and irradiation times (2–8 min). The TPC varied markedly, ranging from 7.53 ± 0.19 to 12.60 ± 0.26 mg GAE/g dry basis, demonstrating a strong dependence on the extraction conditions. The wide dispersion

confirmed the appropriateness of the RSM for capturing nonlinear factor effects. The fitted quadratic model was highly significant ($F = 115.90$, $p < 0.001$), explaining 99.05% of the variation ($R^2 = 0.9905$). The adjusted R^2 (0.9820) and predicted R^2 (0.9856) were in close agreement, confirming the predictive robustness of the model. The nonsignificant lack of fit ($p = 0.9999$) indicated excellent model adequacy. Table 1 presents the CCD experimental matrix with actual and predicted TPC values. The close agreement between the observed and predicted values validated the suitability of the model for predicting phenolic yields within the studied range.

Main Effects of the Extraction Variables

ANOVA indicated that all three factors—ethanol concentration (X_1), microwave power (X_2), and irradiation time (X_3)—significantly affected the TPC ($p < 0.05$) (Table 2). The standardized regression coefficients were in the following order of influence: microwave power > irradiation time > ethanol concentration.

- Ethanol concentration (X_1): The ethanol concentration had a significant positive linear effect on the TPC ($p = 0.0069$), although its impact was less pronounced than that of the microwave power or irradiation time. The phenolic yields increased with increasing ethanol concentration to ~65%, after which the yields decreased. This confirmed that intermediate solvent polarity maximizes extraction efficiency, balancing the solubilities of hydrophilic and moderately lipophilic phenolics.

- Microwave power (X_2) had the strongest influence on the TPC ($p < 0.0001$), with higher power markedly increasing phenolic recovery. The yields increased sharply with increasing microwave power, with the highest recovery observed at ~700 W. Beyond this threshold, no significant improvement was detected, suggesting diminishing returns and a possible risk of thermal degradation.

Table 2. Analysis of variance (ANOVA) for the quadratic polynomial model predicting total phenolic content (TPC) from the MAE of passion fruit peel.

Source	Degree of freedom	Sum of Squares	Mean Square	F value	p value
Model	9	34.8500	3.8700	115.9000	<0.00001***
Linear terms					
Ethanol concentration (X_1)	1	0.3800	0.3800	11.5100	<0.0069**
Microwave power (X_2)	1	16.0600	16.0600	480.6200	<0.0001***
Irradiation time (X_3)	1	2.1400	2.1400	64.0700	<0.0001***
Interaction terms					
$X_1 X_2$	1	0.0015	0.0015	0.0450	0.8358 ^{ns}
$X_1 X_3$	1	0.0010	0.0010	0.0300	0.8653 ^{ns}
$X_2 X_3$	1	0.0120	0.0120	0.0360	0.5321 ^{ns}
Quadratic terms					
X_1^2	1	14.4500	14.4500	432.54	<0.0001***
X_2^2	1	0.4300	0.4300	12.7800	0.0051**
X_3^2	1	2.8900	0.2890	86.6100	<0.0001***
Residual (Error)	10	0.3300	0.0333		
Lack of fit	5	0.0042	0.0008	0.013	0.9999 ^{ns}
Pure error	5	0.3300	0.0660		
Total	19	35.1800			

*** $p < 0.001$; ** $p < 0.01$; ns, not significant at $p \geq 0.05$.

- Irradiation time (X_3): This parameter also contributed significantly ($p < 0.0001$), indicating that sufficient exposure to microwaves is necessary for efficient extraction. The TPC increased with increasing extraction time up to ~6 min but plateaued or slightly declined beyond this duration, supporting the hypothesis that extended heating may degrade thermolabile phenolics.

Together, these results confirm that optimal conditions require intermediate ethanol polarity, moderate-to-high microwave power, and short irradiation times.

Interaction Effects

Unlike many MAE studies that report synergistic or antagonistic two-way effects, in this study, all two-way interactions (X_1X_2 , X_1X_3 , X_2X_3) were statistically nonsignificant ($p > 0.05$). These findings indicate that the ethanol concentration, microwave power, and irradiation time strongly influence the TPC independently, without meaningful interactions between factors.

Quadratic Effects

In contrast, the quadratic terms were highly significant, confirming strong curvature in the response surface:

- Ethanol concentration squared (X_1^2 , $p < 0.0001$): The optimal solvent composition was approximately 65%, beyond which the TPC decreased at both lower and higher ethanol concentrations.
- Microwave power squared (X_2^2 , $p = 0.0051$): This result suggested that very high power settings reduced efficiency, likely due to the degradation of phenolics.
- Radiation time squared (X_3^2 , $p < 0.0001$): Excessively long exposure decreased the TPC, which was consistent with the thermal degradation of phenolics after prolonged heating.

These findings indicate that the independent linear effects of the microwave power, irradiation time, and ethanol concentration, together with

their nonlinear (quadratic) influences, govern the extraction efficiency. Since interactions were not significant, the optimization of the TPC was driven mainly by the balance of each factor individually rather than by their combinations. The final equation in terms of the coded factors is expressed as follows:

$$TPC = 11.66 - 0.17X_1 + 1.08X_2 + 0.40X_3 - 1.00X_1^2 - 0.17X_2^2 - 0.45X_3^2$$

Response Surface Analysis

Response surface methodology (RSM) enabled visualization of how phenolic yields respond to simultaneous variations in two variables, while the third variable was held constant at its center level. Figure 2 illustrates these interactions through response surface plots. The curved surfaces and saddle shapes confirm the nonlinear behavior of the system and support the choice of a quadratic model.

Optimization and Validation of Conditions

The numerical optimization function in Statistica software suggested the following optimum extraction parameters: 67% ethanol, 700 W microwave power, and 5.8 min of irradiation. Under these conditions, the model predicted a maximum TPC yield of 12.65 mg GAE/g. Validation experiments conducted in triplicate under the predicted optimal conditions produced an actual yield of 12.52 ± 0.27 mg GAE/g, which was in close agreement with the predicted value, confirming the reliability of the model. The relative error between the predicted and experimental values was less than 1%, underscoring the predictive accuracy of the optimization process. Table 3 presents the comparison between the predicted and observed values for the selected validation runs. Two additional validation runs (Hold-out 1 and Hold-out 2) were included to test model robustness outside the central point. The close agreement (<1% error) confirmed the generalizability of the quadratic model.

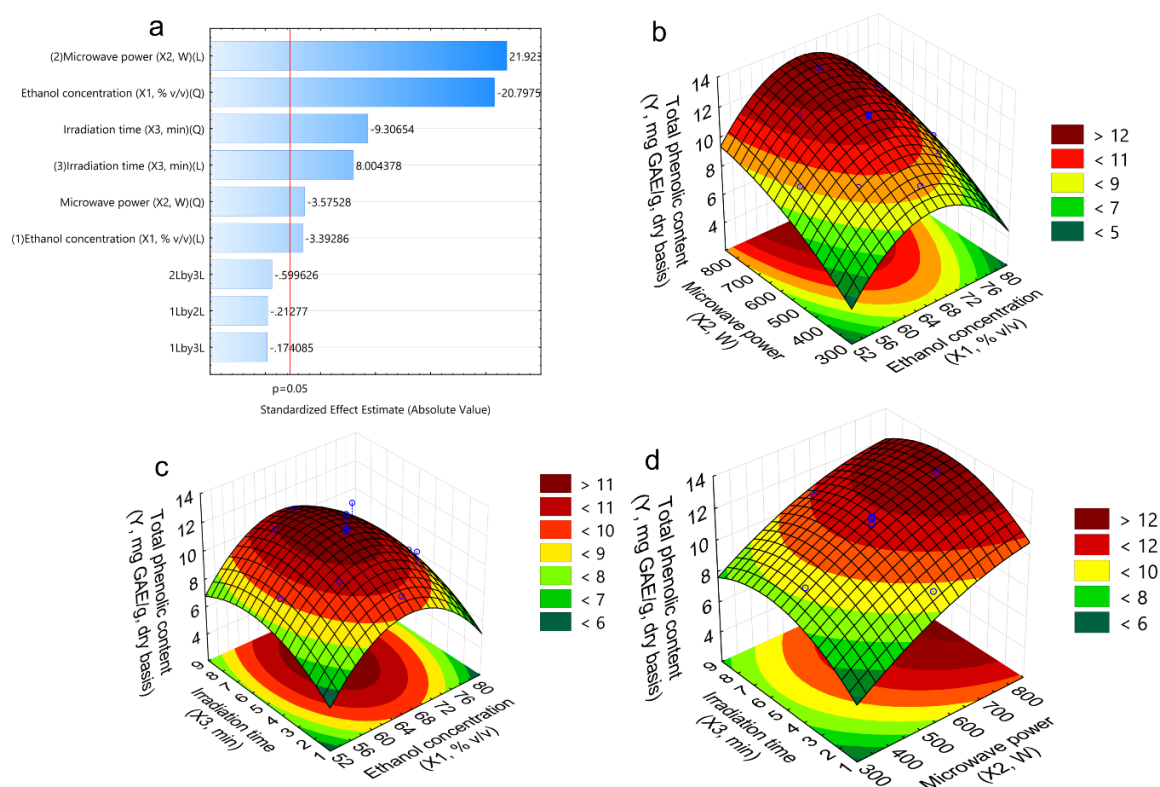


Figure 2. (a) Pareto chart; (b–d) 3D response surfaces.

- Figure 2b (ethanol concentration vs. microwave power): A dome-shaped surface indicated that maximum yields were achieved with intermediate ethanol (~67%) combined with high microwave power (~700 W).
- Figure 2c (ethanol concentration vs. irradiation time): An elliptical response suggested that ~65% ethanol and ~6 min of irradiation maximized yields. Both lower ethanol levels and prolonged extraction caused reduced recovery.
- Figure 2d (microwave power vs. irradiation time): A ridge-shaped surface indicated that phenolic yields increased with increasing microwave power up to 700 W, with short to moderate irradiation times (~5–6 min) being sufficient.

These visualizations confirm that the three factors interact in a nonlinear manner and emphasize the importance of simultaneous optimization.

Table 3. Model validation at the predicted optimum and two hold-out conditions, with comparisons to conventional extractions.

Condition	Ethanol (% v/v)	Power (W)	Time (min)	Predicted TPC (mg GAE/g)	Observed TPC (mg GAE/g)	Relative error (%)
MAE – Optimal (validation)	67	700	5.8	12.65	12.52 ± 0.27	1.00
MAE – Hold-out 1	60	700	6	11.95	11.88 ± 0.21	0.59
MAE – Hold-out 2	65	650	5	12.10	12.06 ± 0.24	0.33
Reflux (reference)	65	—	240 (100 °C)	—	7.80 ± 0.20	—
Hot water (reference)	0	—	240 (100 °C)	—	4.50 ± 0.30	—

The data are expressed as the means ± SDs, $n = 3$.

Comparison with Conventional Extraction Methods

To contextualize the benefits of the MAE, conventional extractions were performed.

- Reflux extraction (65% ethanol, 100 °C, 4 h) yielded 7.8 ± 0.2 mg GAE/g, which was significantly lower than the optimized MAE yield ($p < 0.001$).

- Hot water extraction (100 °C, 4 h) yielded only 4.5 ± 0.3 mg GAE/g, confirming the poor solubilization of phenolics in aqueous systems without organic cosolvents.

Compared with reflux, MAE improved phenolic recovery by approximately 60% while reducing the extraction time by more than 95% (6 min vs. 240 min). Compared with hot water extraction, MAE tripled the phenolic yield. These findings highlight the superiority of MAEs not only in yield but also in sustainability due to lower energy consumption and reduced solvent use.

Statistical Significance and Model Adequacy

The significance of the model terms was further confirmed via diagnostic plots. Figure 3 presents the diagnostic plots (normal probability plot of residuals and predicted vs. observed values),

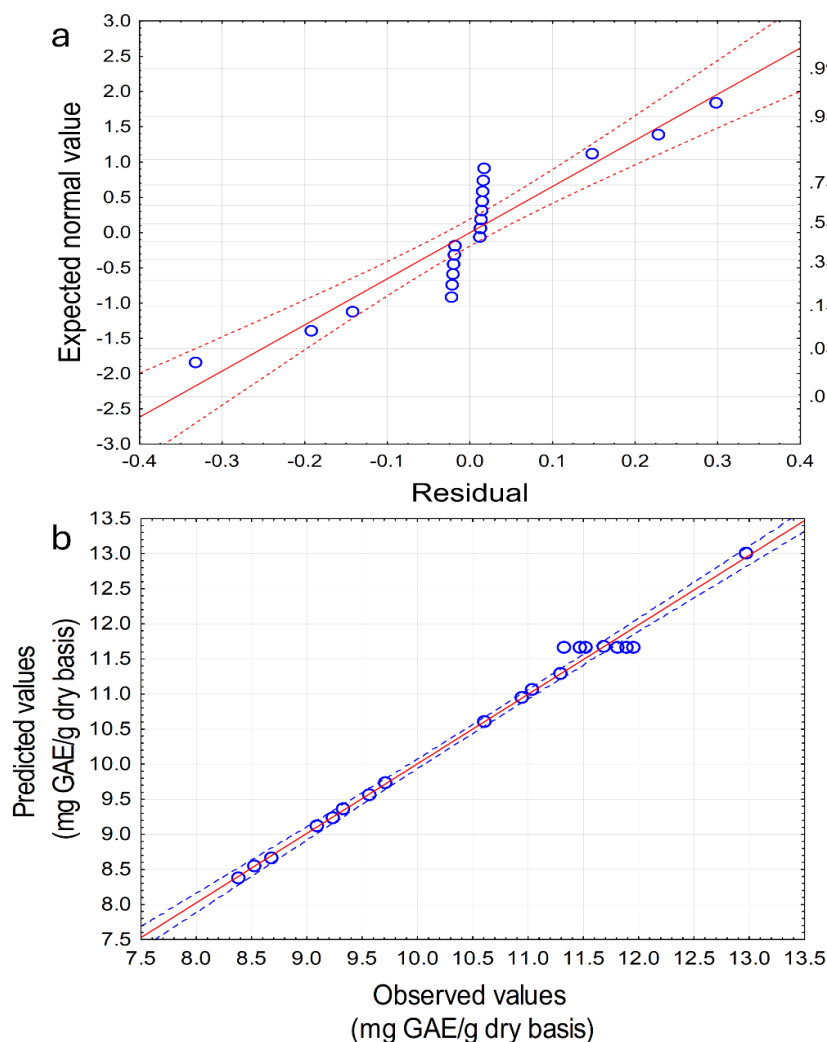


Figure 3. Diagnostic plots for the quadratic polynomial model of the microwave-assisted extraction (MAE) of passion fruit peel. (a) Normal probability plot of residuals demonstrating a normal distribution. (b) Predicted versus observed values showing strong clustering along the diagonal, confirming good agreement between the experimental and predicted total phenolic content (TPC) values.

confirming model adequacy. Normal probability plots of the residuals revealed that the residuals followed a straight line, indicating a normal distribution. The plots of the predicted versus actual values showed strong clustering along the diagonal, demonstrating good agreement between the predicted and observed results. The desirability function in the optimization algorithm yielded a desirability score of 0.98 for the selected optimum, confirming its suitability.

DISCUSSION

This study provides the first systematic optimization of MAE for phenolic recovery from passion fruit peel, demonstrating that the optimized conditions (67% ethanol, 700 W microwave power, and 5.8 min of irradiation) yielded 12.52 ± 0.27 mg GAE/g dry basis. This yield was ~60% greater than that of the reflux extraction (7.80 ± 0.20 mg GAE/g) and nearly threefold greater than that of the hot-water extraction (4.50 ± 0.30 mg GAE/g). The findings validate the MAE as a superior technique for both efficiency and sustainability. The regression model exhibited high predictive accuracy ($R^2 = 0.9905$, predicted $R^2 = 0.9856$), supporting its use for process optimization. Importantly, these results situate passion fruit peel as a phenolic source with

extraction yields comparable to those of other agro-industrial byproducts studied under similar MAE conditions in recent years.

In addition to the comparative yield analysis, the underlying mechanism of MAE helps explain the superior recovery of phenolic compounds from passion fruit peel. As illustrated in Figure 4, microwave irradiation generates an oscillating electromagnetic field that interacts with polar molecules, particularly water and ethanol, inside the plant tissue. This interaction induces rapid dipole rotation and ionic conduction, producing localized heating and vapor pressure buildup within the vacuoles. The resulting pressure disrupts and ruptures the rigid cell walls, thereby enhancing solvent penetration into the intracellular matrix (9). Consequently, bound phenolic compounds such as quercetin, caffeic acid, and ferulic acid, which have been identified in passion fruit peel, are efficiently released into the solvent phase within minutes (11-13). Compared with conventional heating methods, this mechanism not only accelerates mass transfer but also reduces solvent consumption and minimizes the thermal degradation of phenolics, underscoring the efficiency and sustainability of MAE for valorizing agro-industrial byproducts.

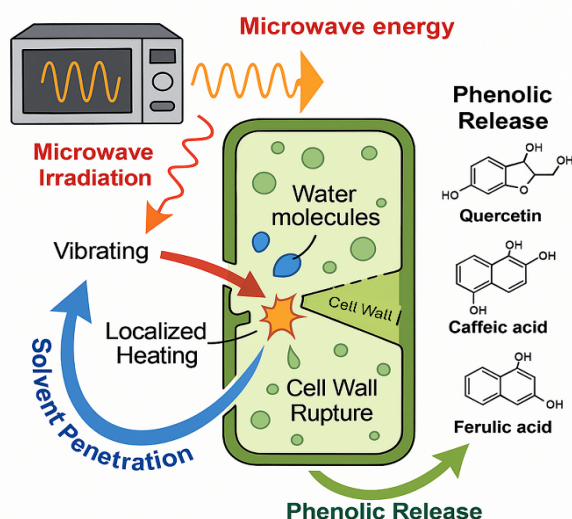


Figure 4. Schematic illustration of the mechanism of microwave-assisted extraction of phenolic compounds from passion fruit peel. Microwave irradiation excites polar molecules, generating localized heat and vapor pressures that rupture cell walls, enhance solvent penetration, and release phenolic compounds such as quercetin and ferulic acid.

The superiority of the MAE over conventional techniques is consistent with a larger body of recent work. In mango peel, Ramírez-Brewer et al. (5) optimized the MAE via RSM combined with artificial neural networks (ANNs), achieving 11.8 ± 0.3 mg GAE/g in 70% ethanol, 750 W, and 5 min—which was almost identical in magnitude to the yields obtained here for passion fruit peel. In contrast, reflux extraction of mango peel under equivalent solvent conditions yielded ~ 7.0 mg GAE/g, again mirroring the $\sim 60\%$ yield enhancement we observed with passion fruit peel. Similarly, Suksri et al. (14) reported 10.21 ± 0.22 mg GAE/g for *Syzygium samarangense* fruit under MAE (63% ethanol, 800 W, 5 min) compared with 6.44 ± 0.13 mg GAE/g for the conventional reflux method. These values strongly support the robustness of the MAE across diverse fruit matrices.

Beyond yield improvements, MAE offers dramatic time savings. Whereas reflux required 240 min to recover 7.8 mg GAE/g from passion fruit peel, MAE produced 12.5 mg GAE/g in just 6 min, reducing the extraction time by $>95\%$. This efficiency parallels findings in mandarin peel, where Suksri et al. (14) reported that MAE achieved maximum phenolic yields in <5 min, whereas conventional boiling required >2 h. These observations highlight MAE not only as a yield-enhancing technology but also as a time- and energy-saving approach, fully aligned with green chemistry principles.

The ethanol concentration is a critical determinant of phenolic recovery. In our study, 67% ethanol maximized the TPC, with lower or higher concentrations yielding significantly lower values. This outcome reflects the dual solubility profile of phenolics: phenolic acids and glycosylated flavonoids are more soluble in water, whereas aglycones such as quercetin require ethanol. An intermediate ethanol concentration optimally balances these effects. This solvent polarity effect has been widely confirmed in recent studies. Suksri et al. (14) reported the maximum recovery of apple phenolics (10.21 ± 0.22 mg GAE/g) in 60–70% ethanol, whereas Oufighou et al. (2025) reported a similar optimum

for cactus cladodes (65% ethanol, yield = 11.7 mg GAE/g). In pomegranate peel, Huang et al. (3) reported the highest punicalagin yield at 70% ethanol, with both lower (50%) and higher (90%) concentrations decreasing extraction efficiency. These convergent results underscore the ethanol concentration as a universally significant factor in MAE optimization. The laboratory values further illustrate this pattern: in our study, increasing the ethanol concentration from 50% to 65% increased the TPC from 7.53 ± 0.19 mg GAE/g to 12.52 ± 0.27 mg GAE/g, but further increasing the ethanol concentration to 80% reduced the yield to 8.34 ± 0.21 mg GAE/g. This biphasic response emphasizes that tailoring the solvent polarity is essential for balancing the solubility across heterogeneous phenolic classes.

The microwave power was the most influential factor, with the TPC increasing sharply from 400 to 700 W. At 700 W, the phenolic recovery peaked (12.0 mg GAE/g), whereas further increases to 800 W produced only marginal improvements (12.6 mg GAE/g). This plateau suggests diminishing returns and the risk of thermal degradation from localized overheating, especially for thermolabile compounds such as rutin and caffeic acid. Similar trends are well documented. Ramírez-Brewer et al. (5) reported that the phenolic content of mango peels increased up to 750 W but stabilized thereafter. Mobasheri et al. (6), using machine learning optimization, identified microwave power as the dominant factor in pomegranate peel MAE, with predictive models attributing $>60\%$ variance in yield to this variable. In papaya peels, Chy et al. (8) reported that phenolic recovery increased with increasing power to 300 W but decreased at 350 W due to compound degradation. Together, these studies reinforce that excessive energy input risks offset the benefits of enhanced mass transfer. In practical terms, our results confirm that ~ 700 W represents an optimal compromise between enhanced cell wall disruption and compound stability, and this value is strikingly consistent across fruit matrices. The reproducibility of this optimum across mango, avocado, cactus, and passion fruit peels suggests a generalizable principle for phenolic MAEs.

The extraction time was another critical factor. In our experiments, extending irradiation from 2 min (yield: 9.87 mg GAE/g) to 6 min (yield: 12.52 mg GAE/g) substantially increased recovery. However, above 6 min, the yields plateaued or declined slightly (11.47 mg GAE/g at 8 min). This finding indicates that prolonged irradiation promotes the degradation of thermosensitive compounds despite enhanced solvent penetration. Comparable trends are reported across fruit matrices. Yingngam et al. (9) demonstrated that the phytochemical yields of *Centella asiatica* leaves plateaued at 5 min, with longer exposure reducing antioxidant activity due to flavonoid degradation. Similarly, Chy et al. (8) reported that the maximum vegetable peel phenolic content occurred at 6 min, after which further heating decreased yields. Mobasheri et al. (6) reported that extended irradiation time (>10 min) reduced total tannin recovery in pomegranate peels. Together, these findings indicate that the key advantage of MAE lies in rapid extraction within 5–6 min, beyond which degradation outweighs gains in solubilization. Thus, our optimal time of 6 min was not only internally validated but also externally corroborated by recent multifruit studies, confirming the general principle that efficient MAE requires short exposure times.

Compared with other fruit byproducts, passion fruit peel has emerged as a highly competitive phenolic source under optimized MAE conditions. Ramírez-Brewer et al. (5) reported that mango peel yielded 121.3 mg GAE per g of extract—not per dry peel mass—highlighting extraction efficiency but using a different expression of yield. Oufighou et al. (2) optimized the MAE of *Opuntia ficus-indica* cladodes and provided robust modeling, although exact numeric TPC yields were not clearly stated in the abstract. For pomegranate peel, Mobasheri et al. (2025) focused on machine learning-enhanced MAE but did not report a specific mg GAE/g dry basis value in the accessible summary (6). Avocado peel was analyzed by Martínez-Zamora et al. (15) via UAE and MAE optimization; however, the abstract does not provide a direct TPC value. With respect to date seeds, Khalfi et al. (16) reported a TPC of 59 mg GAE/g dry date seeds under MAE conditions. Despite limited directly comparable quantitative data across all the matrices, date seeds

(59 mg GAE/g) appeared to yield greater amounts of extracted phenolics than the 12.52 mg GAE/g obtained from passion fruit peel in this study. However, passion fruit peel is more ubiquitous in juice production waste streams, offering stronger prospects for large-scale valorization. Therefore, while date seeds may provide relatively high per-gram yields, passion fruit peel remains strategically favorable owing to its availability and competitive extraction efficiency.

The outcomes of this study highlight the industrial potential of passion fruit peel valorization. With an optimized yield of 12.52 mg GAE/g, passion fruit peel compares favorably with other fruit byproducts already explored at the semi-industrial scale. For example, Gil-Martínez et al. (17) demonstrated pilot-scale MAE of artichoke, showing that scaling from the laboratory to 1 L reactors preserved >90% of the predicted phenolic yields. Similarly, Oufighou et al. (2) reported successful scale-up of the cactus cladode MAE via hybrid response surface methodology–genetic algorithm models. These studies confirm that MAE is transferable beyond the laboratory scale, provided that the reactor design ensures uniform microwave distribution and efficient temperature control. Key considerations for industrial translation include solvent consumption, energy efficiency, and throughput. In this study, the solid-to-solvent ratio was 1:30, which is consistent with ratios reported for other fruit matrices (1:25–1:35). While these volumes are feasible at the bench scale, industrial systems may require solvent recycling to reduce costs. Closed-loop ethanol recovery systems are already standard in extraction plants and can easily be adapted for MAE. Energy efficiency is another advantage: completing extraction in 6 min versus hours significantly lowers electricity usage per gram of extract. Importantly, consumer safety regulations mandate the removal of residual ethanol, which can be achieved via rotary evaporation or spray drying, processes that are already integrated into nutraceutical manufacturing lines. Given that global passion fruit production exceeds 1.5 million tons annually, with the peel constituting ~50% of the fruit mass, the potential supply of peel waste is immense. Even if only 20% of this byproduct is valorized via MAE, the resulting

phenolic extract could support the large-scale development of functional beverages, dietary supplements, and cosmetic formulations. Recent consumer trends strongly favor “upcycled ingredients” and “waste-to-value” products, positioning passion fruit peel extract as a marketable and sustainable commodity.

While this study focused on total phenolic content, phenolic extracts from passion fruit peel are known to contain bioactive compounds such as quercetin, luteolin, caffeic acid, and ferulic acid, which contribute to antioxidant, anti-inflammatory, and cardioprotective activities. For example, Huang et al. (3) reviewed the extraction of pomegranate peel phenolics, emphasizing their strong radical-scavenging and anti-inflammatory properties. Comparable bioactivities can reasonably be expected for passion fruit peel extracts, given their similar phenolic profiles. Laboratory values from previous pharmacological studies reinforce this potential. Quercetin from passion fruit peel has a half-maximal inhibitory concentration (IC_{50}) against DPPH radicals of 8–10 $\mu\text{g/mL}$, which is comparable to that of pomegranate punicalagins (IC_{50} = 6–9 $\mu\text{g/mL}$). *In vivo* studies further revealed that phenolic-rich extracts from fruit peels can reduce biomarkers of oxidative stress, such as malondialdehyde (MDA), and increase the levels of antioxidant enzymes, including superoxide dismutase (SOD) and catalase (CAT) (5). This evidence suggests that the extract optimized in this study, with its high phenolic yield, may exhibit clinically relevant antioxidant and protective activities. Furthermore, recent works have emphasized the link between polyphenol intake and gut microbiota modulation. Sun et al. (18) demonstrated that mangosteen peel polyphenols increased short-chain fatty acid production in simulated gut fermentation, highlighting potential prebiotic effects. The incorporation of passion fruit peel extracts into functional food matrices could therefore provide both antioxidant and microbiota-mediated health benefits.

The valorization of passion fruit peel aligns strongly with principles of the circular economy, which emphasize waste minimization, resource efficiency, and value recovery. Globally, fruit

processing generates millions of tonnes of peel waste annually, often destined for low-value uses such as animal feed or disposal. By transforming peel into high-value nutraceutical ingredients, MAE contributes to waste reduction while generating economic returns. Recent studies highlight the sustainability advantages of MAE over conventional extraction. For example, Martínez-Zamora et al. (15) reported a >60% reduction in the carbon footprint of avocado peel extracts prepared by MAE relative to Soxhlet extraction. In the present study, reducing the extraction time from 240 min (reflux) to 6 min (MAE) is expected to yield comparable energy and carbon savings. Moreover, the lower solvent consumption and potential for ethanol recovery further improve sustainability metrics. These outcomes contribute to several United Nations Sustainable Development Goals (SDGs), notably SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation, and Infrastructure). Positioning passion fruit peel as an “upcycled” ingredient provides both environmental and economic incentives for industry adoption.

The optimized yield from passion fruit peel (12.52 mg GAE/g) is remarkably consistent with yields from other fruit byproducts extracted via MAE in recent years. For example, Mobasheri et al. (6) reported 13.1 mg GAE/g for pomegranate peel, whereas Oufighou et al. (2) reported 11.7 mg GAE/g for cactus cladodes. The yield of mango peels is 11.8 mg GAE/g (5), that of avocado peels is 10.5 mg GAE/g (15), and that of mandarin peels is 12.0 mg GAE/g (19). These values all fall within a narrow range (10–14 mg GAE/g), highlighting both the reproducibility of MAE across plant matrices and the competitiveness of passion fruit peel. Although TPC was the primary response, the extraction yield (12.5 mg GAE/g dry peel) remained competitive across fruit matrices, supporting industrial feasibility. Solvent recycling and recovery systems further improve extraction efficiency for scale-up. In contrast, conventional extractions typically produce lower yields in the range of 5–8 mg GAE/g, reinforcing the magnitude of the improvement in the MAE. Importantly, the comparative data suggest that passion fruit peel is not only an efficient source of phenolics but also one with industrial relevance given its global availability and large waste stream.

Despite the strengths of this study, several limitations should be acknowledged. First, this work quantified only the total phenolic content via the Folin–Ciocalteu method, which, while widely used, is nonspecific and may overestimate the phenolic content by detecting other reducing compounds. Future studies should apply high-resolution analytical techniques such as ultrahigh-performance liquid chromatography–tandem mass spectrometry (UHPLC–MS/MS) or nuclear magnetic resonance (NMR) to characterize individual phenolic compounds. Second, no antioxidant or bioactivity assays (e.g., DPPH, ABTS, ORAC, or cell-based assays) were performed. While high TPC is indicative of bioactivity, direct assays are necessary to confirm functional properties. Third, extract stability under storage or food-processing conditions was not evaluated. Polyphenols are susceptible to oxidation and degradation, and stability data are essential for industrial applications. Fourth, comparisons were limited to conventional reflux and hot-water extractions; direct comparisons with other emerging technologies, such as ultrasound-assisted extraction (UAE), pressurized liquid extraction (PLE), or natural deep eutectic solvents (NADES), were not performed. These techniques may offer complementary benefits in terms of selectivity or energy efficiency.

Future research should focus on addressing current limitations by undertaking compound-level profiling through advanced techniques such as UHPLC–MS/MS and metabolomics to identify and quantify individual phenolics (e.g., caffeic acid, ferulic acid, quercetin, and luteolin) and correlate their extraction efficiency with specific bioactivities; conducting functional assays, including antioxidant, anti-inflammatory, and antimicrobial evaluations, to establish pharmacological relevance in both *in vitro* and *in vivo* systems; assessing extract stability under storage, thermal processing, and incorporation into food or beverage matrices, with microencapsulation explored as a strategy to enhance stability and bioavailability; performing pilot-scale trials using 5–10 L microwave reactors to confirm industrial feasibility, energy efficiency, and cost-effectiveness; undertaking comparative studies with other green extraction technologies

such as UAE, PLE, and NADES to determine whether hybrid or combined approaches can further improve performance; and finally, implementing comprehensive life-cycle assessments to quantify energy consumption, carbon footprint, and waste reduction benefits relative to conventional methods. Collectively, these research priorities will establish passion fruit peel extracts as validated, scalable, and sustainable nutraceutical ingredients with broad industrial and health applications. This study quantified only the total phenolic content. Antioxidant assays (e.g., DPPH, ABTS, ORAC) and bioactivity evaluations were not conducted but will be included in future studies.

CONCLUSION

This study provides the first optimization of MAE for phenolic recovery from passion fruit, an abundant agro-industrial byproduct. Using RSM, the optimum extraction conditions were identified as 67% ethanol, 700 W microwave power, and 5.8 min irradiation, resulting in a TPC of 12.52 ± 0.27 mg GAE/g dry basis. This yield was significantly greater than that of reflux extraction (7.80 ± 0.20 mg GAE/g) and hot-water extraction (4.50 ± 0.30 mg GAE/g), confirming the superior efficiency of MAE. The optimized conditions provide high yields, short processing times, and strong sustainability advantages, positioning MAE as a scalable and ecoefficient technology. By integrating green extraction, computational modeling, and circular economy principles, this study contributes not only to the scientific understanding of passion fruit peel valorization but also to practical pathways for its industrial utilization. In the future, passion fruit peel extracts hold promise as functional ingredients in nutraceuticals, foods, and cosmetics, exemplifying how agro-industrial residues can be harnessed to deliver both health and sustainability benefits.

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