

Multi-response optimization of convective drying of Keitt mango peel: balancing techno-functional performance and antioxidant retention in a value-added flour

Optimización multirrespuesta del secado convectivo de la cáscara de mango Keitt: equilibrio entre el rendimiento tecnofuncional y la retención de antioxidantes en una harina de valor añadido

Ramona Julieta Espinoza-Moreno¹ ; Georgina Vizcarra-Félix¹ ; Xóchitl Ariadna Ruiz-Armenta² ; María Fernanda Quintero-Soto¹ ; Oscar Daniel Argüelles-López² ; Fernando Salas-López³ ; Mario Armando Gómez-Favela^{2*} 

¹Ingeniería Agroindustrial, Universidad Politécnica del Mar y la Sierra (UPMYS), Carretera a Potrerillos del Norte Km 3, La Cruz, Elota, Sinaloa, México. C.P. 80027.

²Programa de Posgrado en Ciencia y Tecnología de Alimentos, Facultad de Ciencias Químico Biológicas, Universidad Autónoma de Sinaloa, Calz. de las Américas Nte. 2771, Cd. Universitaria, Col. Burócrata, Culiacán, Sinaloa, México. C.P. 80030.

³Departamento de Ciencias de la Salud, Universidad Autónoma de Occidente, UR Culiacán. Blvd. Lola Beltrán y Blvd. Rolando Arjona, 4 de marzo, Culiacán, Sinaloa, México. C.P. 80020.

ABSTRACT

Mango peel, a by-product of pulp dehydration, is rich in fiber and phytochemicals. Its conversion into flour requires drying conditions that balance functionality and antioxidant retention. This study aimed to optimize drying temperature (DT) and drying time (Dt) to produce mango peel flour (*Mangifera indica* L.) cv. Keitt with desirable techno-functional properties, carotenoid content, and lipophilic antioxidant activity. Convective drying was modeled using a central composite design, with DT ranging from 50 to 80 °C and Dt from 8 to 36 h. The water absorption index (WAI), water solubility index (WSI), oil absorption index (OAI), total carotenoid content (TC), and lipophilic antioxidant activity measured using ABTS (L_{ABTS}) and DPPH (L_{DPPH}) assays were simultaneously optimized. All reduced models were significant ($p < 0.0001$), showed no significant lack of fit, and explained 86.2–94.7% of the variability in the responses. Increasing temperature negatively affected WAI, TC, L_{ABTS} , and L_{DPPH} , whereas it increased WSI. The optimal combination was DT = 50 °C and Dt = 36 h, with an overall desirability of 0.905. Compared with untreated peel, the flour exhibited higher WAI, WSI, OAI, and dispersibility, retaining 75.0% of TC, 83.9% of L_{ABTS} , and 85.8% of L_{DPPH} . These findings demonstrate that drying at a moderate temperature improves techno-functional properties and promotes the retention of carotenoids and lipophilic antioxidant activity.

Keywords: *Mangifera indica*; agro-industrial by-product; response surface methodology; hot-air drying

RESUMEN

La cáscara de mango, subproducto del deshidratado de la pulpa, es rica en fibra y compuestos fitoquímicos. Su transformación en harina requiere condiciones de secado que equilibren la funcionalidad y la retención de antioxidantes. El objetivo fue optimizar la temperatura (DT) y el tiempo (Dt) de secado para obtener harina de cáscara de mango (*Mangifera indica* L.) cv. Keitt con buenas propiedades tecnofuncionales, contenido de carotenoides y actividad antioxidante lipofílica. El secado convectivo se modeló mediante un diseño central compuesto, con DT de 50–80 °C y Dt de 8–36 h. Se optimizaron simultáneamente los índices de absorción de agua (WAI), solubilidad en agua (WSI) y absorción de aceite (OAI), los carotenoides totales (TC) y la actividad antioxidante lipofílica mediante ABTS (L_{ABTS}) y DPPH (L_{DPPH}). Los modelos reducidos fueron significativos ($p < 0.0001$), sin falta de ajuste, y explicaron entre 86.2 y 94.7% de la variabilidad. La temperatura afectó negativamente WAI, TC, L_{ABTS} y L_{DPPH} , mientras que incrementó WSI. La combinación óptima fue DT = 50 °C y Dt = 36 h, con deseabilidad global de 0.905. Frente a la cáscara sin tratar, la harina presentó mayores WAI, WSI, OAI y dispersabilidad, y retuvo 75.0% de TC, 83.9% de L_{ABTS} y 85.8% de L_{DPPH} . Estos resultados demuestran que el secado a temperatura moderada mejora las propiedades tecnofuncionales y favorece la retención de carotenoides y actividad antioxidante lipofílica.

Palabras clave: *Mangifera indica*; subproducto agroindustrial; metodología de superficie de respuesta; secado con aire caliente

INTRODUCTION

Mango (*Mangifera indica* L.) is processed into juices, pulps, dried products, and preserves, generating peel and seed streams that can represent a substantial fraction of the original fruit. Disposal of these materials loses potentially valuable constituents and adds handling and environmental costs. Mango peel is particularly relevant because it contains dietary fiber, pectin, carotenoids, phenolic acids, flavonoids, gallotannins, and xanthones, although composition varies with cultivar, maturity, growing conditions, and processing history (Jahurul et al., 2015; Marçal & Pintado, 2021; Gupta et al., 2022; Kućuk et al., 2024). Converting peel into a shelf-stable powder is consequently one of the most direct strategies for returning this biomass to the food chain.

Mango peel powders may contribute water- and oil-binding capacity, soluble solids, color, and fiber-associated phenolics to food formulations. Bound phenolics are particularly important because solvent extraction alone may substantially underestimate the phenolic fraction associated with the cell-wall matrix (Ajila & Prasada-Rao, 2013). Peel powders have been explored in cereal and bakery systems, but their successful use depends not only on chemical composition but also on particle hydration, solubility, dispersibility, and stability (Larrauri et al., 1996; Serna-Cock et al., 2015; Marçal & Pintado, 2021). Thus, characterizing both technological and phytochemical attributes is necessary before proposing a peel flour as a food ingredient.

Drying is required to reduce perishability and facilitate milling, yet it simultaneously changes matrix structure and bioactive compounds. Tissue disruption and concentration can increase extractability or expose water- and oil-interaction sites, whereas oxygen and heat can promote carotenoid isomerization and oxidation and degrade or transform phenolic compounds. Studies comparing freeze, vacuum, infrared, and hot-air drying have shown that the direction and magnitude of these changes depend on the drying method and response evaluated (Dorta et al., 2012; Sogi et al., 2013; Akther et al., 2023). Recent reviews likewise identify optimization of mango-peel drying as a prerequisite for obtaining powders that retain phytochemicals without sacrificing technological performance (Marçal & Pintado, 2021; Kućuk et al., 2024).

Most previous studies have compared discrete drying methods or temperatures. Such comparisons are useful but do not explicitly resolve the trade-off among multiple quality targets. A condition that maximizes

solubility may not preserve carotenoids, while a condition selected only for antioxidant retention may require excessive time or yield a powder with less favorable hydration. Response surface methodology and desirability functions provide a rational framework to quantify the simultaneous effects of process variables and select a compromise among responses (Derringer & Suich, 1980).

This study aimed to model and optimize the effects of convective-drying temperature and time on the techno-functional properties, total carotenoids, and lipophilic antioxidant capacity of mango (*Mangifera indica* L.) cv. Keitt peel flour.

MATERIALS AND METHODS

RAW MATERIAL AND PRETREATMENT

Mango (*Mangifera indica* L.) cv. Keitt peels were obtained from the Damaya dehydration plant, located in El Saladito, Elota, Sinaloa, Mexico. Peels were washed with potable water, immersed in chlorinated water (20 ppm) for 3 min, blanched at 95 °C for 2 min, drained on absorbent paper for 15 min, sealed in plastic bags, and stored at 4 °C/12 h until drying.

EXPERIMENTAL DESIGN AND CONVECTIVE DRYING

A rotatable central composite design evaluated drying temperature (X_1 = 50–80 °C) and drying time (X_2 = 8–36 h). The design comprised four factorial points, four axial points, and five center-point runs, giving 13 experimental runs (Table 1). Each run used a 100 g batch of pretreated peel cut into pieces of approximately 4 X 2 X 0.3 cm for length, width, and thickness, respectively. Samples were distributed on waxed paper over stainless-steel trays (80 X 50 cm by length and width, respectively), leaving a space of approximately 1 cm between columns, and were dried in a CRAFT HFA-1200 DPT oven with forced convection (airflow not specified by the manufacturer).

Dried peels of each treatment were milled using a Hamilton Beach 80350R grinder, obtaining a particle size <250 µm. Flours were sealed in plastic bags and refrigerated at 4 °C/30 days until analysis. All response values were expressed on a dry basis unless otherwise stated.

WATER ABSORPTION INDEX (WAI) AND WATER SOLUBILITY INDEX (WSI)

WAI and WSI were measured according to Ruiz-Armenta et al. (2022). Flour

Table 1. Central composite design for convective drying of mango (*Mangifera indica* L.) cv. Keitt peel.

Treatment	X ₁	X ₂
1	54	12
2	76	12
3	54	32
4	76	32
5	50	22
6	80	22
7	65	8
8	65	36
9	65	22
10	65	22
11	65	22
12	65	22
13	65	22

X₁= Drying temperature (°C), X₂= Drying time (h)

(2.5 g) was suspended in 30 mL distilled water at 30 °C, agitated at 250 rpm for 30 min, and centrifuged at 3000 × g and 25 °C for 10 min. The sediment was weighed, and WAI was calculated by equation (1), and expressed as grams of gel formed per gram of sample. The supernatant was transferred to a pre-weighed vessel and dried at 110 °C for 12 h. WSI was calculated from the recovered soluble solids by equation (2), and expressed as a percentage of the original dry solids. Measurements were performed in triplicate.

$$WAI \left(\frac{\text{g gel formed}}{\text{g sample}} \right) = \frac{W_g - W_i}{W_s} \quad (1)$$

$$WSI(\%) = \frac{W_F - W_v}{W_s} \times 100 \quad (2)$$

Where W_g = weight of gel, W_i = initial sample weight, W_F = Final weight (glass + dry solids), W_v = glass weight, W_s = initial sample weight.

OIL ABSORPTION INDEX (OAI) AND DISPERSIBILITY

For OAI, flour (0.5 g) was mixed with 3 mL vegetable (Cristal®) oil, vortexed for 1 min, held for 30 min, and centrifuged at 1600 × g and 25 °C for 25 min

according to Chandra et al. (2015) with some modifications. The amount of absorbed oil was calculated using the equation (3):

$$OAI = \frac{(V_1 - V_2)}{\text{g sample}} \quad (3)$$

Where V_1 is the initial oil volume and V_2 is the final oil volume, expressed as mL of oil absorbed per gram of sample. The test was performed in triplicate.

Dispersibility was determined according to Mora-Escobedo et al. (1991). Flour (1 g) was suspended in 10 mL deionized water, homogenized at 10,000 rpm for 5 min using a homogenizer (T18 Basic Ultra-Turrax, IKA, UK), and allowed to stand for 30 min. The phase that remained dispersed was measured visually, and the volume was reported as a percentage. Measurements were performed in triplicate.

TOTAL CAROTENOIDS

The procedure was performed using the method reported by Rodriguez-Amaya and Kimura (2004). One gram of sample was weighed, rehydrated with 5 mL of deionized water, and allowed to stand for 30 min on a Vari-Mix shaker. Subsequently, 10 mL of acetone was added, and the mixture was homogenized for 15 min using the Vari-Mix equipment. After homogenization, the mixture was vacuum-filtered through Whatman No. 40 filter paper. The extract was collected, and the residue was extracted again using 5 mL of acetone. This procedure was repeated until the residue became colorless. Next, one-third of the recovered extract volume was transferred, and 7 mL of petroleum ether and 20 mL of distilled water were added without shaking to prevent emulsion formation.

The mixture was allowed to stand for 15 min to permit phase separation. The aqueous phase was discarded, and the petroleum ether phase was collected. This process was repeated twice, each time using one-third of the filtered extract volume. The absorbance of the extract was measured at 450 nm using a spectrophotometer (UV-GENESYS model 10, Series AQ7-2H7G229001, Thermo Electron Scientific Instruments LLC, Madison, Wisconsin, USA). Total carotenoids were calculated following the equation (4) and expressed as µg of total carotenoids per g of dry sample:

$$TC \left(\frac{\mu\text{g}}{\text{g}} \right) = \frac{A_e \cdot V_e \cdot 10^4}{\frac{A_{1\%}}{1\text{cm}} \cdot W_s} \quad (4)$$

Where A_e = Absorbance of extract, V_e = Total volume (mL), $\frac{A_{1\%}}{1\text{cm}}$ = Absorption

coefficient of carotenoids in petroleum ether in a cell with a 1 cm path length (2500), W_s = sample weight (g).

LIPOPHILIC ANTIOXIDANT CAPACITY

The petroleum-ether carotenoid extract was used for the lipophilic assays. For ABTS assay, the radical cation was generated by reacting ABTS solution with $K_2S_2O_8$ and incubating the mixture for 16 h in darkness according to Re et al. (1999) with slight modifications, then ABTS activated radical was adjusted until absorbance of 0.7 ± 0.02 . Subsequently, an aliquot of 75 μ L of extract (or standard curve point) was combined with 2925 μ L ABTS radical-cation working solution, reacted for 5 min at room temperature, and measured at 734 nm using a spectrophotometer (UV-GENESYS model 10, Series A07-2H7G229001, Thermo Electron Scientific Instruments LLC, Madison, Wisconsin, EE.UU.). For DPPH (Brand-Williams et al., 1995), 200 μ L extract was mixed with 1800 μ L of 150 μ M DPPH in methanol, incubated at room temperature for 30 min, and measured at 510 nm using a spectrophotometer (UV-GENESYS model 10, Series A07-2H7G229001, Thermo Electron Scientific Instruments LLC, Madison, Wisconsin, EE.UU.).

A Trolox standard curve was used with concentrations of 25, 50, 100, 200, 400, 500, 600, 800 and 1000 ppm for ABTS and DPPH. Results were expressed as μ mol Trolox equivalents (TE)/100 g dry sample.

RESPONSE SURFACE MODELING AND OPTIMIZATION

Each response was initially fitted to a second-order polynomial (equation 5):

$$Y_k = \beta_{k0} + \beta_{ki} X_i + \beta_{kj} X_j + \beta_{kij} X_i^2 + \beta_{kjj} X_j^2 + \beta_{kij} X_i X_j + \epsilon \quad (5)$$

where X_i and X_j are coded drying temperature (DT) and drying time (Dt), respectively. The response variables used were water absorption index (WAI), water solubility index (WSI), oil absorption index (OAI), total carotenoids (TC), lipophilic ABTS (L_{ABTS}) and lipophilic DPPH (L_{DPPH}), aiming to maximize the values of WAI, WSI, TC, L_{ABTS} and L_{DPPH} , while minimizing the values of OAI. Non-significant terms ($p > 0.10$) were removed while preserving model hierarchy where applicable. Model reduction was performed by backward elimination of terms with $p > 0.10$, while preserving model hierarchy throughout the procedure. This threshold was used as a selection criterion to obtain parsimonious models and limit the premature removal of potentially relevant effects contributing to the description of the response surface. The elimination criterion was distinguished from the

significance threshold of $p < 0.05$ used for statistical interpretation. The adequacy of the reduced models was assessed through residual analysis, lack-of-fit testing, and comparison of their goodness-of-fit and predictive performance measures with those of the full models. Model adequacy was assessed using the model p-value, lack-of-fit test, R^2 , adjusted R^2 , predicted R^2 , and coefficient of variation. The numerical desirability method was used for optimization and obtaining the best combination of independent variables, which is based on a geometric average of the individual desirabilities of the response variables, obtaining a global desirability value (D) through the equation (6):

$$D = (d_1 * d_2 * d_3 * d_4 * d_5 * d_6)^{\frac{1}{6}} \quad (6)$$

An acceptable value for global desirability (D) should be between 0.6 and 0.8, being $D = 1$ the ideal optimum value (Ruiz-Armenta et al., 2022). Analyses were performed in Design-Expert 7.0.

STATISTICAL ANALYSIS

Data were compared by one-way analysis of variance (ANOVA) followed by Tukey's test at $p < 0.05$ using Statgraphics Plus 5.1 (Statistical Graphics Corporation, Rockville, MD, USA). All analytical determinations were performed in triplicate.

RESULTS AND DISCUSSION

MODEL ADEQUACY

All six reduced models were significant ($p < 0.0001$) and showed non-significant lack of fit (Table 2). The coefficients of determination ranged from 0.8619 for WAI to 0.9466 for WSI, while predicted R^2 values ranged from 0.7808 to 0.8044. For every response, the difference between adjusted and predicted R^2 was below 0.20, and the coefficient of variation was below 8%. Collectively, these statistics indicate that the models adequately described response variability within the experimental domain. The resulting regression equations and their corresponding response contours are presented in equations (7-12) and in Figure 1, respectively.

$$Y_{WAI} = 6.52 - 0.24 X_1 - 0.14 X_2 \quad (7)$$

$$Y_{WSI} = 14.52 + 1.60 X_1 + 1.40 X_2 + 5.77 X_1^2 + 4.13 X_2^2 \quad (8)$$

$$Y_{OAI} = 1.25 + 0.079 X_1 - 0.049 X_2 + 0.17 X_1 * X_2 \quad (9)$$

Table 2. Coded regression coefficients and adequacy statistics for the response models.

Coefficient	WAI	WSI	OAI	TC	LABTS	LDPPH
Intercept						
β_0	6.52	14.52	1.25	42.24	587.83	750.22
Linear						
β_1	-0.24***	1.60**	0.079***	-3.46***	-91.76***	-76.49***
β_2	-0.14**	1.40**	-0.049***	NS	-3.29***	NS
Interaction						
$\beta_1\beta_2$	NS	NS	0.17***	NS	NS	NS
Quadratic						
β_1^2	NS	5.77***	NS	NS	NS	-47.69***
β_2^2	NS	4.13***	NS	NS	NS	39.41***
P_{model}	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.8619	0.9466	0.9097	0.8749	0.8769	0.9374
Adjusted R^2	0.8343	0.9199	0.8796	0.8499	0.8523	0.9061
Predicted R^2	0.7929	0.8044	0.7857	0.8009	0.7808	0.8042
Lack of fit	0.5994	0.2695	0.6317	0.8095	0.5148	0.4586
CV (%)	1.55	7.61	3.66	2.77	5.23	3.41

WAI= Water absorption index, WSI= Water solubility index, OAI= Oil absorption index, TC= Total carotenoids, LABTS= Lipophilic ABTS, LDPPH= Lipophilic DPPH. NS= nonsignificant. *p < 0.05;

** p < 0.01; *** p < 0.001.

$$Y_{TC} = 42.24 - 3.46 X_1 - 0.17 X_2 \quad (10)$$

$$Y_{LABTS} = 587.83 - 91.76 X_1 - 3.29 X_2 \quad (11)$$

$$Y_{LDPPH} = 750.22 - 76.49 X_1 - 3.49 X_2 - 47.69 X_1^2 + 39.41 X_2^2 \quad (12)$$

Based on these mathematical models, surface response plots were generated for each evaluated response, as shown in Figure 1 A-F. In these figures, the effects of the factors (X_1 = DT and X_2 = Dt) on response variables (WAI, WSI, OAI, TC, LABTS, and LDPPH) can be observed, showing in blue the areas where the lowest values were obtained and in red the areas where the highest values were obtained.

HYDRATION, SOLUBILITY, AND OIL ABSORPTION

WAI ranged from 6.1597 to 6.9823 g gel formed/g sample and decreased as drying temperature and time increased. The highest experimental value was obtained at 54 °C/12 h, whereas the lowest was recorded at 80 °C/22 h (Table 3). Water absorption could be due to the abundance and accessibility of hydrophilic sites, matrix porosity, particle size, and the structural state of fiber-associated polysaccharides (Kalla-Bertholdt et al., 2023). Thermomechanical treatments can disrupt compact fiber structures and improve hydration properties (Zhai et al., 2022). Conversely, higher drying temperatures or prolonged drying may damage the fiber network and promote pore collapse (Sungsinchai et al., 2017). Drying-induced associations between cellulose fibrils, involving hydrogen bonding, may

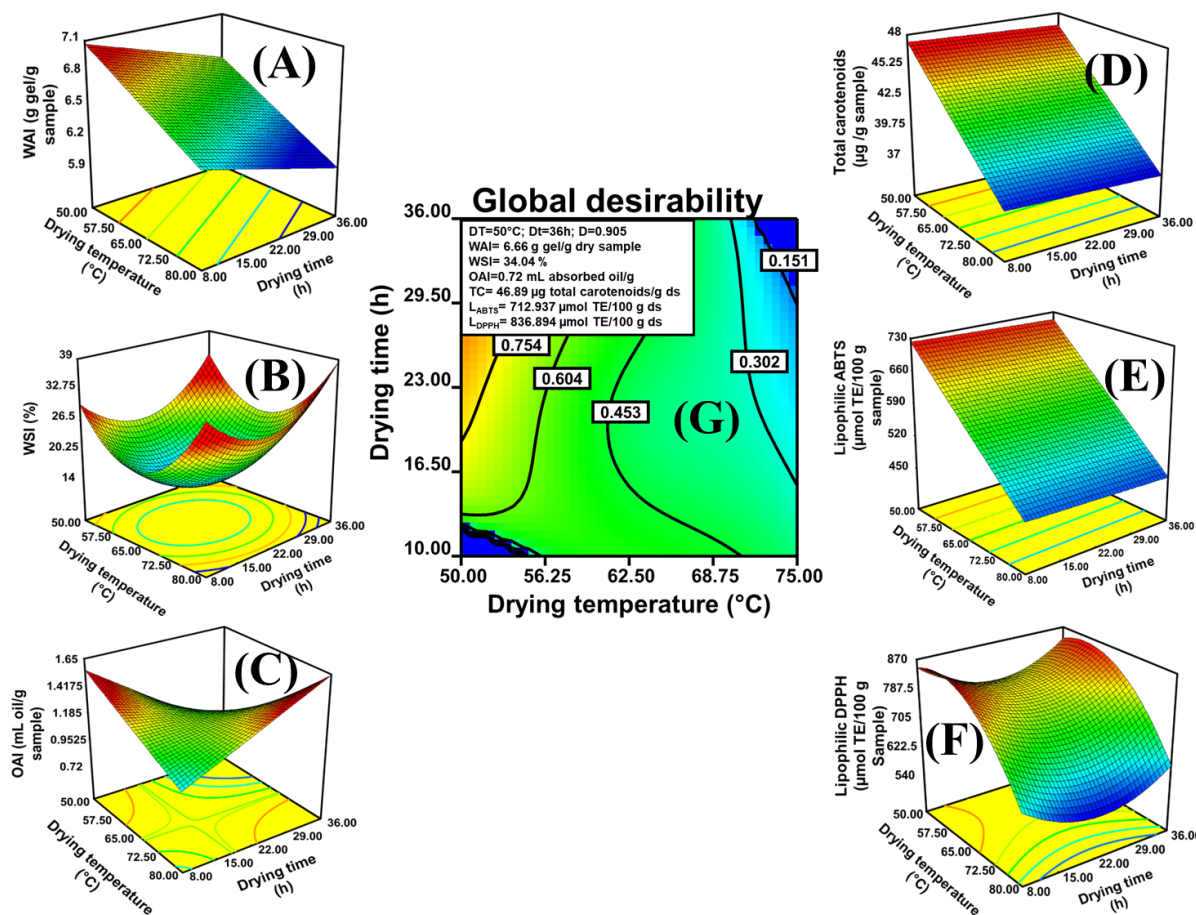


Figure 1. Model-predicted contour plots for (A) water absorption index, (B) water solubility index, (C) oil absorption index, (D) total carotenoids, (E) lipophilic ABTS capacity, (F) lipophilic DPPH capacity, and (G) global desirability with optimal combination of factor values and predicted values.

further restrict rehydration through hornification (Luo & Zhu, 2011). The negative effects observed in this study therefore suggest that structural changes at the upper temperature and time levels outweighed any improvement in the accessibility of water-binding sites.

The observed WAI values were within or slightly above the 4.68–6.05 g gel formed/g sample range reported by Sogi et al. (2013) for mango-peel powders produced by freeze-, cabinet-, vacuum-, and infrared-drying. This comparison supports the strong hydration capacity of Keitt mango peel flour, although it does not establish superiority over other drying methods because cultivar, pretreatment, particle size, fiber composition, and analytical conditions can substantially affect water uptake. Marçal et al. (2026) similarly showed that hot-air drying modified the water- and oil-interaction properties of mango peel even when total dietary fiber was largely preserved. Accordingly, the changes in WAI are more plausibly

associated with reorganization of the cell-wall matrix and alteration of pore accessibility than with fiber concentration alone.

WSI ranged from 12.784 to 29.512%, this parameter was affected by the positive linear and quadratic terms of both drying factors (Tables 2 and 3). The response surface therefore indicates a curved relationship rather than a simple proportional increase with temperature or time. Thermal disruption may release soluble sugars, pectic material, and other low-molecular-weight constituents; conversely, extensive heating can promote aggregation, structural collapse, or formation of less-soluble associations. The comparatively wide variation among the center-point observations (12.784–16.041%) should be considered when interpreting this response because it directly contributes to the estimation of pure error.

Table 3. Experimental responses for convective drying of mango (*Mangifera indica* L.) cv. Keitt peel.

Treatment	WAI	WSI	OAI	TC	L _{ABTS}	L _{DPPH}
1	6.9823	20.504	1.3984	46.905	658.72	795.91
2	6.5025	23.097	1.1540	38.588	534.36	659.11
3	6.7005	22.549	0.9831	45.030	668.94	809.87
4	6.1752	26.548	1.4350	37.523	467.00	634.52
5	6.8208	25.097	1.1066	46.648	725.94	777.92
6	6.1597	29.512	1.4040	38.273	437.62	565.93
7	6.7826	22.005	1.3637	42.209	609.03	852.23
8	6.4006	26.064	1.1831	43.320	630.82	840.00
9	6.5771	12.784	1.2111	40.313	619.49	731.50
10	6.3788	13.716	1.2733	41.200	544.17	751.85
11	6.3198	14.689	1.3067	42.156	560.48	768.10
12	6.5341	16.041	1.1817	43.021	602.81	779.58
13	6.4495	15.363	1.2478	43.900	582.44	720.05

WAI= Water absorption index (g gel formed/g dry sample), WSI= Water solubility index (%), OAI= Oil absorption index (mL absorbed oil/g sample), TC= Total carotenoids (μg of total carotenoids/g dry sample), L_{ABTS}= Lipophilic ABTS (μmol Trolox equivalent (TE)/100 g dry sample), L_{DPPH}= Lipophilic DPPH (μmol Trolox equivalent (TE)/100 g dry sample).

Drying-dependent differences in solubility have also been reported for mango-peel powders. Sogi et al. (2013) observed the greatest solubility in freeze-dried material, whereas Marçal et al. (2026) documented changes in technological properties after hot-air drying. These findings support the interpretation of WSI as an integrated response to composition and drying-induced structure, rather than as a direct measure of soluble dietary fiber. In the present design, the higher values predicted near the experimental boundaries should therefore be interpreted within the evaluated temperature–time region and not extrapolated to more severe conditions.

OAI ranged from 0.9831 to 1.4350 mL absorbed oil/g sample and was influenced by the linear effects of temperature and time and by their interaction (Table 3). Oil retention can involve both physical entrapment within pores and capillaries and interactions with exposed nonpolar sites. The significant interaction indicates that these mechanisms depended on the combined thermal history rather than on either drying factor

independently. Because composition, porosity, and particle-size distribution were not characterized in detail, the observed response cannot be attributed to a single structural mechanism.

The experimental OAI range was higher than 0.11 mL absorbed oil/g sample reported by Dereje and Girma (2020) for mango cv. Keitt peel drying at 50 °C/90 min using a fluidized bed dryer. Variation in oil type, centrifugation conditions, particle size, cultivar, and the proportions of protein, lignin, and insoluble fiber may account for this difference. Moreover, a higher OAI is not intrinsically advantageous: it may favor flavor retention and mouthfeel in some formulations, but it can also increase the amount of oil retained by the ingredient and potentially exposed to oxidation. The technological relevance of the values obtained here must therefore be evaluated in a specific food matrix under realistic processing and storage conditions.

TOTAL CAROTENOIDS AND LIPOPHILIC ANTIOXIDANT CAPACITY

Total carotenoids ranged from 37.523 to 46.905 μg of total carotenoids/g dry sample (Table 3). Drying temperature exerted a strong negative linear effect, whereas drying time was nonsignificant in the reduced model. Carotenoids are susceptible to oxidation and geometric isomerization during exposure to heat, oxygen, and light; therefore, the negative temperature coefficient is consistent with previous reports of carotenoid losses during thermal drying of mango materials (Sogi et al., 2013; Marçal & Pintado, 2021; Akther et al., 2023). Within the conditions studied, temperature was consequently more influential than treatment duration in determining the measurable carotenoid content.

The response of carotenoids to drying is strongly matrix-dependent. De Ancos et al. (2018) showed that individual carotenoids responded differently to hot-air and freeze-drying in mango peel and paste, even within the same cultivar, demonstrating that processing effects cannot be generalized across by-products. Fratianni et al. (2020) also reported better carotenoid preservation in mango fruit dried at 50 °C than under more severe thermal conditions. These observations support selection of the lower-temperature region in the present optimization. Nevertheless, spectrophotometric determination reflects the combined absorbance of the extracted pigments and cannot distinguish degradation from cis-trans isomerization or altered extractability. The temperature coefficient should therefore be interpreted as a net effect on measurable total carotenoids rather than as degradation kinetics for a specific compound.

Lipophilic ABTS (L_{ABTS}) capacity ranged from 437.62 to 725.94 $\mu\text{mol TE}/100\text{ g}$ dry sample and decreased with both drying factors, with temperature producing the larger effect (Table 3). Lipophilic DPPH (L_{DPPH}) capacity ranged from 565.93 to 852.23 $\mu\text{mol TE}/100\text{ g}$ dry sample and showed significant curvature for temperature and time (Table 3). Although both assays estimate radical-scavenging capacity, they differ in radical chemistry, reaction medium, steric accessibility, and reaction kinetics. Their response surfaces should therefore be regarded as complementary descriptions of the lipophilic extract rather than interchangeable measurements.

The negative temperature effects on total carotenoids, L_{ABTS} , and L_{DPPH} suggest that pigment loss or transformation contributed to reduced lipophilic radical-scavenging capacity. However, total-carotenoid measurements cannot resolve individual compounds or exclude

contributions from other lipophilic antioxidants; chromatographic profiling is needed to identify retained, transformed, or degraded constituents. Associations between phytochemical content and antioxidant activity also depend on drying conditions, extraction procedures, and assay chemistry (Akther et al., 2023).

The differing ABTS and DPPH response surfaces may reflect their distinct reactivities: ABTS reacts with diverse compounds in aqueous and organic environments, whereas DPPH is typically measured in organic media and is sensitive to molecular accessibility and reaction time. Consistent with Floegel et al. (2011), these differences are not contradictory but may indicate changes in antioxidant composition or accessibility detected differently by each assay. Neither assay identifies the compounds responsible for the activity.

MULTI-RESPONSE OPTIMIZATION

The desirability function simultaneously maximized WAI, WSI, TC, L_{ABTS} , and L_{DPPH} while minimizing OAI. The highest predicted global desirability ($D = 0.905$) was obtained at 50 °C/36 h (Figure 1G). According with Ruiz-Armenta et al. (2022), an acceptable value for global desirability (D) should be between 0.6 and 0.8, being $D = 1$ the ideal optimum value; therefore, the overall desirability in the present work can be considered very good and close to ideal. This condition represents a compromise among responses: the lower temperature favored retention of carotenoids and lipophilic antioxidant capacity, whereas the longer drying time contributed to the WSI target. At 50 °C/36 h, the models predicted WAI of 6.66 g gel formed/g sample, WSI of 34.04%, OAI of 0.72 mL absorbed oil/g sample, TC of 46.89 μg of total carotenoids/g dry sample, L_{ABTS} of 712.94 $\mu\text{mol TE}/100\text{ g}$ dry sample, and L_{DPPH} of 836.89 $\mu\text{mol TE}/100\text{ g}$ dry sample.

The global desirability is a relative measure of performance within the defined experimental region and the selected optimization criteria; it does not imply that every response reached its individual optimum at 50 °C/36 h. This distinction is important because the responses followed different, and in some cases opposing, trends. The practical relevance of the selected condition therefore depends on the relative importance assigned to each response and on experimental agreement with the predicted values. Reporting the individual predictions alongside the global desirability makes the compromise transparent and identifies the attributes that contributed to selection of the final condition.

TECHNO-FUNCTIONAL PROPERTIES OF THE SELECTED FLOUR

Drying at 50 °C/36 h substantially modified the technological behavior of mango peel flour (Table 4). Compared with untreated flour, WAI increased from 1.37 to 6.77 g gel formed/g sample, WSI from 15.32 to 33.41%, and dispersibility from 36.66 to 64.16%. The WAI of the optimized flour was comparable to values reported for dietary fiber obtained from convectively dried Hilacha mango peel and for freeze-dried powders from different mango cultivars (Hincapié et al., 2014; Serna-Cock et al., 2015). The increases in hydration and dispersibility suggest improved interaction with aqueous systems and may facilitate incorporation into liquid or semisolid foods. Nevertheless, performance in a formulated product cannot be inferred solely from these measurements.

OAI also increased, from 0.19 to 0.73 mL absorbed oil/g sample. This result does not contradict the optimization criterion because OAI was minimized among the dried flours predicted within the experimental domain, rather than constrained to remain below the value of untreated flour. Drying and milling may have exposed hydrophobic sites or changed capillary structure, thereby increasing oil retention. This explanation remains provisional because the associated changes in composition, porosity, and particle-size distribution were not measured.

Taken together, the increases in WAI, WSI, OAI, and dispersibility indicate a broad modification of powder-solvent interactions. Potential contributors include cell-wall rupture, redistribution of soluble solids, changes in pore structure, and exposure of polar and nonpolar binding sites. Marçal et al. (2026) similarly reported that hot-air drying altered mango-peel technological properties alongside modest changes in fiber-carbohydrate composition, reinforcing the view that bulk composition alone does not predict functionality. Higher WAI and dispersibility could be advantageous in hydrated formulations, while increased OAI may be relevant where retention of lipophilic flavor components is desired. These potential applications should be confirmed in food systems under appropriate pH, ionic strength, shear, and storage conditions.

RETENTION OF LIPOPHILIC ATTRIBUTES AND VALORIZATION IMPLICATIONS

Relative to untreated peel flour, processing at 50 °C/36 h retained 75.0% of total carotenoids (51.88 vs 38.93 µg of total carotenoids/g dry sample), 83.9% of L_{DPPH} capacity (880.78 vs 739.13 µmol TE/100 g dry sample), and

85.8% of L_{DPPH} capacity (918.54 vs 788.13 µmol TE/100 g dry sample) (Table 4). Thus, drying did not enhance the lipophilic antioxidant fraction; instead, it limited the losses associated with processing while improving several technological properties. This distinction provides a more accurate description of the performance of the selected condition.

Evidence from previous studies indicates that carotenoids can be more sensitive than bulk phenolic measurements to thermal drying, although the magnitude and direction of change depend on the mango matrix. De Ancos et al. (2018) observed different carotenoid responses in peel and paste subjected to the same drying treatments, while Fratianni et al. (2020) identified temperature as an important determinant of carotenoid retention in dried mango fruit. The 75.0% retention observed here should therefore be regarded as a process-specific result for Keitt mango peel. Similarly, retention of 83.9–85.8% of lipophilic antioxidant capacity indicates limited functional loss but does not demonstrate preservation of every contributing molecule. Cultivar-dependent differences in mango-peel carotenoid and phenolic profiles further limit direct transfer of absolute values among varieties or geographic origins (Marcillo-Parra et al., 2021).

Overall, the observed trade-off supports the use of multi-response optimization. Selecting conditions solely to maximize WSI could favor higher temperatures and greater phytochemical loss, whereas selection based only on carotenoids could overlook flour functionality and completion of the drying process. Future optimization should incorporate final moisture or water activity, drying yield, color, and energy consumption. These variables are necessary to determine whether the selected laboratory condition can be translated into a safe, stable, and economically feasible ingredient process (Marçal & Pintado, 2021; Gupta et al., 2022; Kučuk et al., 2024).

CONCLUSIONS

Drying temperature and time significantly affected the techno-functional and lipophilic antioxidant attributes of Keitt mango peel flour. The response models adequately represented the experimental domain, and multi-response optimization selected 50 °C/36 h as the best predicted compromise ($D = 0.905$). Compared with untreated flour, flour produced under the optimized condition showed greater water absorption, water solubility, oil absorption, and dispersibility while retaining 75.0% of total carotenoids and 83.9–85.8% of lipophilic antioxidant capacity. Overall, mild-

temperature convective drying improved the hydration and dispersion properties of Keitt mango peel flour while limiting losses of lipophilic antioxidant attributes.

ACKNOWLEDGEMENTS

The authors thank the Universidad Politécnica del Mar y la Sierra as well as the Universidad Autonoma de Sinaloa for providing the necessary spaces for the completion of this work.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

DECLARATION OF AI USE

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) for language editing, reference-format checking, and improvement of structural clarity. The authors subsequently reviewed and edited all AI-assisted content and take full responsibility for the scientific accuracy and integrity of the final manuscript

Table 4. Techno-functional properties, total carotenoids and lipophilic capacity of untreated and optimal dehydrated mango (*Mangifera indica* L.) cv. Keitt peel flours.

Property	Untreated	Optimized flour (50 °C/36 h)	Predicted values	Change (%)
Techno-functional				
WAI (g gel formed/g sample)	1.37 ± 0.06 ^b	6.77 ± 0.31 ^a	6.66 ± 0.55 ^a	+394.2
WSI (%)	15.32 ± 0.59 ^b	33.41 ± 0.39 ^a	34.04 ± 10.26 ^a	+118.1
OAI (mL absorbed oil/g dry sample)	0.19 ± 0.01 ^b	0.73 ± 0.07 ^a	0.72 ± 0.31 ^a	+284.2
Dispersibility (%)	36.66 ± 1.44 ^b	64.16 ± 1.44 ^a	NA	+75.0
TC (µg carotenoids/g dry sample)	51.88 ± 0.53 ^a	38.93 ± 1.71 ^b	46.89 ± 6.41 ^{ab}	
Antioxidant activity				
L _{ABTS} (µmol TE/100 g dry sample)	880.78 ± 31.29 ^a	739.13 ± 24.54 ^b	712.94 ± 168.63 ^{ab}	-16.1
L _{DPPH} (µmol TE/100 g dry sample)	918.54 ± 32.01 ^a	788.13 ± 23.53 ^b	836.89 ± 166.42 ^{ab}	-14.2

^{a,b}Different letters indicated significant differences ($p < 0.05$) between means in same row. NA= Not applicable, WAI= water absorption index, WSI= water solubility index; OAI= oil absorption index; TC= total carotenoids; L_{ABTS}= lipophilic capacity evaluated by ABTS assay; L_{DPPH}= lipophilic capacity evaluated by DPPH assay.

REFERENCES

- Ajila, C. M., & Prasada-Rao, U. J. S. (2013). Mango peel dietary fibre: Composition and associated bound phenolics. *Journal of Functional Foods*, 5(1), 444–450. <https://doi.org/10.1016/j.jff.2012.11.017>
- Akther, S., Jothi, J. S., Badsha, M. R., Rahman, M. M., Das, G. B., & Alim, M. A. (2023). Drying methods effect on bioactive compounds, phenolic profile, and antioxidant capacity of mango powder. *Journal of King Saud University – Science*, 35(1), 102370. <https://doi.org/10.1016/j.jksus.2022.102370>
- Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of a free radical method to evaluate antioxidant activity. *LWT – Food Science and Technology*, 28(1), 25–30. [https://doi.org/10.1016/S0023-6438\(95\)80008-5](https://doi.org/10.1016/S0023-6438(95)80008-5)
- de Ancos, B., Sánchez-Moreno, C., Zacarías, L., Rodrigo, M. J., Sáyago-Ayerdi, S., Blancas-Benítez, F. J., Domínguez-Avila, J. A., & González-Aguilar, G. A. (2018). Effects of two different drying methods (freeze-drying and hot air-drying) on the phenolic and carotenoid profile of 'Ataulfo' mango by-products. *Journal of Food Measurement and Characterization*, 12, 2145–2157. <https://doi.org/10.1007/s11694-018-9830-4>
- Dereje, B., & Girma, A. (2020). Effect of pretreatments and drying methods on the rehydration ratio of dried mango (*Mangifera indica* L.) slices and evaluation of some properties of its peel flours. *Food Science and Quality Management*, 96, 1–10. <https://doi.org/10.7176/FSQM/96-01>
- Derringer, G., & Suich, R. (1980). Simultaneous optimization of several response variables. *Journal of Quality Technology*, 12(4), 214–219. <https://doi.org/10.1080/00224065.1980.11980968>
- Dorta, E., Lobo, M. G., & González, M. (2012). Using drying treatments to stabilise mango peel and seed: Effect on antioxidant activity. *LWT – Food Science and Technology*, 45(2), 261–268. <https://doi.org/10.1016/j.lwt.2011.08.016>
- Floegel, A., Kim, D. O., Chung, S. J., Koo, S. I., & Chun, O. K. (2011). Comparison of ABTS/DPPH assays to measure antioxidant capacity in popular antioxidant-rich US foods. *Journal of Food Composition and Analysis*, 24(7), 1043–1048. <https://doi.org/10.1016/j.jfca.2011.01.008>
- Fратиани, A., Adiletta, G., Di Matteo, M., Panfili, G., Niro, S., Gentile, C., Farina, V., Cinquanta, L., & Corona, O. (2020). Evolution of carotenoid content, antioxidant activity and volatiles compounds in dried mango fruits (*Mangifera indica* L.). *Foods*, 9(10), 1424. <https://doi.org/10.3390/foods9101424>
- Gupta, A. K., Gurjar, P. S., Beer, K., Pongener, A., Ravi, S. C., Singh, S., Verma, A., Singh, A., Thakur, M., Tripathy, S., & Verma, D. K. (2022). A review on valorization of different byproducts of mango (*Mangifera indica* L.) for functional food and human health. *Food Bioscience*, 48, 101783. <https://doi.org/10.1016/j.fbio.2022.101783>
- Hincapié, G. A., Vásquez, D. C., Galicia, V. S., & Hincapié, C. A. (2014). Propiedades técnico-funcionales de la fibra dietaria de cáscaras de mango variedad Hilacha (*Mangifera indica* L.): Efecto del secado por convección. *Biotechnología en el Sector Agropecuario y Agroindustrial*, 12(1), 153–160. <https://revistas.unicauca.edu.co/index.php/biotechnologia/article/view/311>
- Jahurul, M. H. A., Zaidul, I. S. M., Ghafoor, K., Al-Juhaimi, F. Y., Nyam, K. L., Norulaini, N. A. N., Sahena, F., & Mohd Omar, A. K. (2015). Mango (*Mangifera indica* L.) by-products and their valuable components: A review. *Food Chemistry*, 183, 173–180. <https://doi.org/10.1016/j.foodchem.2015.03.046>
- Kalla-Bertholdt, A. M., Baier, A. K., & Rauh, C. (2023). Potential of modification of techno-functional properties and structural characteristics of citrus, apple, oat, and pea dietary fiber by high-intensity ultrasound. *Foods*, 12(19), 3663. <https://doi.org/10.3390/foods12193663>
- Rodríguez-Amaya, D. B., & Kimura, M. (2004). HarvestPlus handbook for carotenoid analysis. HarvestPlus Technical Monograph 2. International Food Policy Research Institute and International Center for Tropical Agriculture, Washington, DC and Cali.
- Kučuk, N., Primožič, M., Kotnik, P., Knez, Ž., & Leitgeb, M. (2024). Mango peels as an industrial by-product: A sustainable source of compounds with antioxidant, enzymatic, and antimicrobial activity. *Foods*, 13(4), 553. <https://doi.org/10.3390/foods13040553>
- Larrauri, J. A., Rupérez, P., Borroto, B., & Saura-Calixto, F. (1996). Mango peels as a new tropical fibre: Preparation and characterization. *LWT*

- Food Science and Technology, 29(8), 729-733. <https://doi.org/10.1006/fstl.1996.0113>
- Luo, X., & Zhu, J. Y. (2011). Effects of drying-induced fiber hornification on enzymatic saccharification of lignocelluloses. *Enzyme and Microbial Technology*, 48(1), 92-99. <https://doi.org/10.1016/j.enzmictec.2010.09.014>
- Marçal, S., & Pintado, M. (2021). Mango peels as food ingredient/additive: Nutritional value, processing, safety and applications. *Trends in Food Science & Technology*, 114, 472-489. <https://doi.org/10.1016/j.tifs.2021.06.012>
- Marçal, S., Vilas-Boas, A. A., Campos, D. A., & Pintado, M. (2026). Effect of freeze drying, hot air drying, and hot air drying preceded by freezing on phytochemical composition, antioxidant capacity, and technological properties of mango peels. *Foods*, 15(2), 333. <https://doi.org/10.3390/foods15020333>
- Marcillo-Parra, V., Anaguano, M., Molina, M., Tupuna-Yerovi, D. S., & Ruales, J. (2021). Characterization and quantification of bioactive compounds and antioxidant activity in three different varieties of mango (*Mangifera indica* L.) peel from the Ecuadorian region using HPLC-UV/VIS and UPLC-PDA. *NFS Journal*, 23, 1-7. <https://doi.org/10.1016/j.nfs.2021.02.001>
- Mora-Escobedo, R., Paredes-López, O., & Gutiérrez-López, G. F. (1991). Effect of germination on the rheological and functional properties of amaranth seeds. *LWT - Food Science and Technology*, 24(3), 241-244.
- Ruiz-Armenta, X. A., Ruiz-Armenta, J. E., Espinoza-Moreno, R. J., Gutiérrez-Dorado, R., Aguilar-Palazuelos, E., Zazueta-Morales, J. J., & Gómez-Favela, M. A. (2022). Use of sesame by-product and optimized extrusion to obtain a functional flour with improved techno-functional, nutritional and antioxidant properties. *Acta Universitaria*, 32, e3494. <http://doi.org/10.15174.au.2022.3494>
- Re, R., Pellegrini, N., Proteggente, A., Pannala, A., Yang, M., & Rice-Evans, C. (1999). Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free Radical Biology and Medicine*, 26(9-10), 1231-1237. [https://doi.org/10.1016/S0891-5849\(98\)00315-3](https://doi.org/10.1016/S0891-5849(98)00315-3)
- Serna-Cock, L., Torres-León, C., & Ayala-Aponte, A. (2015). Evaluación de polvos alimentarios obtenidos de cáscaras de mango (*Mangifera indica*) como fuente de ingredientes funcionales. *Información Tecnológica*, 26(2), 41-50. <https://doi.org/10.4067/S0718-07642015000200006>
- Sogi, D. S., Siddiq, M., Greiby, I., & Dolan, K. D. (2013). Total phenolics, antioxidant activity, and functional properties of 'Tommy Atkins' mango peel and kernel as affected by drying methods. *Food Chemistry*, 141(3), 2649-2655. <https://doi.org/10.1016/j.foodchem.2013.05.053>
- Sungsinchai, S., Niamnuy, C., Jaree, A., & Devahastin, S. (2017). Influences of pretreatment and drying methods on composition, micro/molecular structures and some health-related functional characteristics of dietary fibre powder from orange pulp residues. *International Journal of Food Science & Technology*, 52(10), 2217-2229. <https://doi.org/10.1111/ijfs.13501>
- Zhai, X., Ao, H., Li, W., Zheng, J., Li, X., & Ren, D. (2022). Physicochemical and structural properties of dietary fiber from *Rosa roxburghii* pomace by steam explosion. *Journal of Food Science and Technology*, 59, 2381-2391. <https://doi.org/10.1007/s13197-021-05254-7>