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# Optimization of the drying process of the chicozapote fruit (*Manilkara zapota* L.) on the techno-functional and nutraceutical properties

# Optimización del proceso de secado del fruto de chicozapote (*Manilkara zapota* L.) sobre las propiedades tecno-funcionales y nutracéuticas

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## ABSTRACT

Chicozapote is an endemic fruit in Mexico, which is also little known and consumed. This fruit has a high content of nutrients and bioactive compounds that could be used to improve the nutraceutical value of other foods as a source of such compounds. However, chicozapote fruit has a short shelf life. One of the most used conservation processes is drying, which offers less susceptibility to microbial degradation. Therefore, optimizing the drying process to produce functional flour with good techno-functional and nutraceutical properties was decided. This study aimed to optimize the drying process of processed chicozapote flour (OPCF) to preserve its techno-functional and nutraceutical properties using a rotatable central composite design of the response surface. Obtained data indicate that the best combination of drying process variables to obtain OPCF with better values for Oil Absorption Index, Water Absorption and Solubility Index, Antioxidant Activity, Total Anthocyanins, and Total Phenolics, were observed at a drying temperature and time of 74.1 °C and 12 h, respectively. Therefore, it is concluded that optimization of the drying process generated beneficial effects on the functional chicozapote flour.

**KEY WORDS:** . Antioxidant activity; Total phenolic compounds; Total anthocyanins; Functional foods; Optimization.

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## RESUMEN

El chicozapote es una fruta endémica de México, poco conocida y consumida. Esta fruta tiene un alto contenido de nutrientes y compuestos bioactivos que podrían utilizarse para mejorar el valor nutracéutico de otros alimentos al ser una fuente de obtención de compuestos. Sin embargo, el chicozapote tiene una vida útil muy corta. Uno de los procesos más utilizados de conservación es el secado al brindarnos menor susceptibilidad a la degradación microbiana. Por lo tanto, decidimos optimizar el proceso de secado para producir una harina funcional con buenas propiedades tecnofuncionales y nutracéuticas. El objetivo de este estudio fue optimizar el proceso de secado sobre las propiedades tecno-funcionales y nutracéuticas de una harina procesada de chicozapote (OPCF) utilizando un diseño compuesto central rotable de superficie de respuesta. Los resultados obtenidos en este estudio indican que la mejor combinación de variables del proceso de secado para obtener la HPOC, con mejores valores en el Índice de Absorción de Aceite, el Índice de Absorción y Solubilidad en Agua, la Actividad Antioxidante, Antocianinas Totales y Fenólicos Totales, se observó a una temperatura de secado de 74.1 °C y un tiempo de 12 h, respectivamente. Por lo que concluimos que la optimización del proceso de secado genero efectos beneficiosos en la harina funcional de chicozapote.


**PALABRAS CLAVE:** Actividad antioxidante; Compuestos fenólicos totales; Antocianinas totales; Alimentos funcionales; Optimización.

## Introduction

The chicozapote (*Manilkara zapota* L.), is a tropical fruit considered a berry that fluctuates in shape from spherical to conical. Its mesocarp is fleshy, rich in starch and coloring pigments, with cells loaded with aromatic oils. The skin is rough and brown when green, becoming smooth as it ripens, while the soft, fleshy, juicy pulp is very sweet, releasing a mild and pleasant fragrance (Vargas y Vargas *et al*., 2015). Worldwide, India is the leading production country with plantations of approximately 163,210 hectares with yields of 8.7 tons/ha, while in Mexico it is distributed in 13 states with plantations of 2,138 ha, with yields of 7.37 tons/ha (SIAP, 2024). In Mexico, this tree is known primarily for its nutritional use, while in other countries its main contribution is the latex extraction, used to produce chewing gum (García-Cuevas *et al*., 2021). Traditionally, it has been used to treat coughs, diarrheal ulcers, hemorrhages, muscle spasms, pain, lung diseases, and neuronal disorders, among other medical conditions (Bashir, 2019). In the specific case of the chicozapote, it presents nutritional interest as it is a source of carotenoids, phenols, vitamins C and A, which are nutritional compounds with potential protective effects due to their antioxidant

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activity. Additionally, it possesses a high nutrient content such as carbohydrates, proteins, fats, fiber, and minerals (Punia-Bangar *et al*., 2022). As a fruit, it is consumed fresh when fully ripe, serving as a dessert fruit in many areas. After being cut from the plant, it continues its ripening process, exhibiting a climacteric pattern. Its shelf life at room temperature is very short, reaching its commercial maturity around 6-8 days after cutting. Within one or two days, it enters an advanced ripening stage, entering the senescence phase, making it highly perishable and challenging for conservation and commercialization (Rivas-Gastelum *et al*., 2023).

Food is lost or wasted throughout the entire food chain, from initial agricultural production to final consumption in households. In general terms, the Food and Agriculture Organization (FAO) estimates that around one-third of the food produced for human consumption is worldwide lost or wasted, equivalent to 1050 million tons per year (FAO, 2013). A significant portion of this loss is due to the lack of suitable means of storage or processing. This underscores the importance of developing appropriate conservation processes that also preserve the nutritional value present in the food (Espinoza-Moreno *et al*., 2021).

One of the most used processes in the industry is drying. This method is one of the oldest methods of food preservation, allowing for reduced susceptibility to microbial degradation. Additionally, it reduces the volume and weight of the raw material, resulting in a significant reduction in packaging, storage, and transportation costs (Serna-Cock *et al*., 2015). Hence, this study aimed to optimize the drying of chicozapote fruit to obtain flour with good techno-functional and nutraceutical properties.

## Material and methods

### Materials

Chicozapote fruits from the El Saladito area, Elota, Sinaloa, were used (geographical coordinates, 23.8833 N, 106.85 W). The fruits were harvested when ripe and with no signs of biological or mechanical damage.

### Production of optimized processed chicozapote flour (OPCF)

For the drying process, the chicozapote fruits were washed and disinfected. Subsequently, the peel was removed, and the fruits were sliced (0.4 cm) and placed on stainless steel trays. These trays were then placed inside a heating oven (ECOSHEL, 9023A) under conditions of drying temperature (DT) and drying time (Dt) according to the different combinations provided by the experimental design. Dehydrated fruits obtained from each treatment were ground using a coffee grinder, resulting in 13 corresponding dehydrated chicozapote flours. Subsequently, these flours were evaluated for the response variables: Oil Absorption Index (OAI), Water Absorption Index (WAI), Water Solubility Index (WSI), Antioxidant Activity (AoxA), Total Anthocyanin Content (TAC), and Total Phenolic Content (TPC).

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## Oil Absorption Index, Water Absorption Index, and Water Solubility Index

OAI, WAI, and WSI were assessed according to Ruiz-Armenta *et al*. (2022). Briefly, samples of 0.5 g of flour were mixed with 3 mL of vegetable oil and were vortexed for 1 minute, left to stand for 30 minutes, and finally centrifuged (1,600xg/25ºC/25 min). The volume of free oil was measured. The amount of absorbed oil was calculated by subtracting the volume of free oil from the initial volume of oil and expressed as mL of absorbed oil per gram of flour. The test was performed in triplicate. For WAI and WSI, samples of 1 g flour were mixed with 15 mL of distilled water at 25 °C and then shaken for 30 min. Then, the mixture was centrifuged (3000xg/25°C/ 10 min) and the supernatant and precipitate were recovered. The supernatant obtained after the WAI assay was decanted in a crystal vessel, evaporated in a stove (80°C/12 h), and then weighed. WAI and WSI were expressed as percentages of dry solids.

## Quantification of Total Anthocyanin Content

To determine the total anthocyanin content (TAC), a hydroalcoholic extract was prepared by mixing 1 g of the sample with 10 mL of 80 % cold ethanol (-20°C), as described by Abdel-Aal and Hucl (1999). The mixture was homogenized (500 rpm/30 min) and centrifuged (10,000xg/ 10 min). The supernatant obtained after centrifugation was used to measure absorbance at 535 nm and 700 nm. TAC was calculated and the results were expressed as milligrams of cyanidin-3-glucoside equivalents per gram of dry weight (mg C3GE/g dw) according to equation 1.

$$TAC = \left(\frac{A_{535} - A_{700}}{\varepsilon}\right) * T_V * PW * \left(\frac{1}{SW}\right) \ldots (1)$$

Where ε = Molar absorption coefficient of cyanidin-3-glucoside (25,965 $cm^{-1}$ $M^{-1}$), Tv = Total volume (mL), MW = Molecular weight of cyanidin-3-glucoside (449.2 g/mol), SW = Sample weight (g).

## Extraction Quantification of Total Phenolic Content

For the determination of Total Phenolic Content (TPC), methanolic extracts were prepared following the method described by Quintero-Soto *et al.* (2022). 500 mg of sample was mixed with 20 mL of 80 % methanol and subjected to agitation (60 min/300 rpm). Subsequently, the samples were hydrolyzed (2 N HCl, 30 min/90°C) and centrifuged (10,000xg/30 min). The supernatant was washed with 40 mL of hexane, then mixed with water (20 mL) and ethyl acetate (40 mL). Phenolic compounds were recovered from ethyl acetate through evaporation. Dried samples were stored at -20°C until use.

The TPC was determined following the method described by Singleton *et al*. (1999). To 0.2 mL of the extract, 2200 µL of Folin-Ciocalteu reagent was added, and the mixture was maintained for 3 minutes in darkness. Subsequently, 60 µL of a 7 % (w/v) sodium carbonate solution was added, followed by incubation for 90 minutes. The absorbance of the samples

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was measured at 765 nm. The results were expressed as milligrams of Gallic Acid equivalents/ 100 grams of dry weight (mg GAE/100 g, dw).

### Antioxidant activity (AoxA)

The *in vitro* antioxidant activity (AoxA) was determined using the ABTS assay (Quintero-Soto *et al*., 2022). A 7.4 mmol/L ABTS radical solution was prepared by mixing ABTS with 2.6 mmol/L potassium persulfate and then incubated for 16 hours in the dark at room temperature (25°C). The ABTS radical solution was then diluted with 10 mmol/L phosphate buffer (pH 7.4) to achieve an absorbance of 0.70 ± 0.02 at 734 nm. Subsequently, 3 mL of the solution was mixed with 0.75 mL of the sample and incubated at room temperature for 6 minutes before recording readings at 734 nm. The antioxidant activity (AoxA) was expressed as µmol Trolox equivalents (TE)/100 g of sample (dw).

### Experimental design

A rotatable central composite experimental design (response surface methodology, RSM) with two factors (process variables) (drying temperature [X1 = DT, 40 °C to 80 °C]/ drying time [X2 = Dt,7 h to 22 h]) and five variation levels (2 factorial [coded: -1, +1], 2 axials [coded: -1.414 (-α), +1.414 (+α)], and 1 central [coded: 0]) was used to obtain the process variables combination throwing 13 treatments (Table 1). The values for the levels of the independent variables were determined based on preliminary trials. The dependent variables in this study were the water Absorption Index (WAI), Water Solubility Index (WSI), Oil Absorption Index (OAI), Antioxidant Activity (AoxA), Total Anthocyanin Content (TAC), and Total Phenolic Content (TPC).

## Optimization

The drying process was optimized to find maximum values of WAI, WSI, AoxA, TPC, and TCA, and minimum values of OAI using the numerical method. The stepwise regression procedure was applied, and non-significant terms ($p > 0.1$) were deleted from a second-order polynomial. Subsequently, a new polynomial is calculated until a predictive model is obtained for each response variable. The statistical software Design Expert 7.0.0 was used for the RSM analyses**.**

## Obtaining and experimental evaluation of the optimized processed chicozapote flour (OPCF)

Once the best temperature and time conditions were determined, the selected model was experimentally validated by drying the fruit under the predicted optimal conditions: a temperature of 74.1 ºC and a drying time of 12 hours. After obtaining the dehydrated fruits, they were ground in a coffee grinder, resulting in an optimized processed chicozapote flour (OPCF). Finally, OPCF was packed in polyethylene bags and stored at room temperature. After obtaining OPCF, it was

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characterized based on its techno-functional and nutraceutical properties. (WAI, WSI, OAI, AoxA, TPC, and TAC).

**Table 1. Experimental design (13 treatments) and experimental results of water absorption index (WAI), water solubility index (WSI), oil absorption index (OAI), total phenolic compounds (TPC), Total anthocyanin content (TAC), and antioxidant activity (AoxA) from optimized processed chicozapote flour (OPCF).**

| Treatments | Process variables[1] | | Response variables[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DT (°C) | Dt (h) | WAI | WSI | OAI | TPC | TAC | AoxA |
| 1 | 45.86 | 9.20 | 0.33 | 35.14 | 1 | 197.33 | 67.54 | 26.588 |
| 2 | 45.86 | 19.80 | 0.84 | 44.49 | 0.8 | 400.10 | 132.89 | 58.601 |
| 3 | 74.14 | 9.20 | 1.97 | 50.84 | 1 | 510.40 | 138.84 | 60.602 |
| 4 | 74.14 | 19.80 | 2.76 | 54.76 | 0.7 | 276.77 | 100.88 | 42.584 |
| 5 | 60.00 | **7.00** | 0.96 | 40.74 | 1.1 | 303.18 | 105.151 | 45.501 |
| 6 | 60.00 | **22.00** | 2.18 | 50.67 | 1.1 | 396.15 | 124.79 | 47.699 |
| 7 | **40.00** | 14.5 | 0.67 | 38.56 | 1 | 399.27 | 113.58 | 40.934 |
| 8 | **80.00** | 14.5 | 2.56 | 52.02 | 0.5 | 499.93 | 121.86 | 49.402 |
| 9 | 60.00 | 14.5 | 1.94 | 51.31 | 1.2 | 542.76 | 123.53 | 54.618 |
| 10 | 60.00 | 14.5 | 1.92 | 50.82 | 1 | 432.87 | 127.77 | 43.884 |
| 11 | 60.00 | 14.5 | 1.58 | 50.63 | 1 | 448.04 | 143.98 | 50.317 |
| 12 | 60.00 | 14.5 | 1.92 | 51.23 | 1 | 453.66 | 125.80 | 48.500 |
| 13 | 60.00 | 14.5 | 1.65 | 48.37 | 1 | 440.50 | 126.40 | 54.067 |

[1]DT = Drying temperature; Dt = Drying time; [2]WAI = Water absorption index (g of gel/g sample); WSI = Water solubility index (%); OAI = Oil absorption index (g of gel/g oil); TPC = Total phenol compounds (mg of gallic acid equivalents [GAE]/100g sample); AoxA = Antioxidant activity (mmol of Trolox equivalents [TE]/100g sample).

## Statistical analysis

The techno-functional and nutraceutical properties data was subjected to a one-way analysis of variance (ANOVA), and mean comparisons were conducted using the least significant difference method (LSD, Least Significant Difference) with a confidence level of 95 %, using the STATGRAPHICS plus Software version 5.1 (Statistical Graphics CorporationTM, Rockville, Maryland, EUA).

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## Results and discussion

### Response surface methodology (RSM) analysis

### Modeling of response variables

The optimized flours obtained from the drying process exhibited different techno-functional and nutraceutical properties. The maximum and minimum values obtained for each response are shown in Table 1. Additionally, Table 2 shows the analysis of variance for the responses WAI, WSI, OAI, AoxA, TAC, and TPC. It is observed that the data exhibited a significant regression model, with $R^2$ values ≥ 0.71, coefficient of variation CV < 13.88, F-value p < 0.0084, and no lack-of-fit.

### Water Absorption Index

Table 2 displays the statistical models for each evaluated response variable, noting that time ($p$ < 0.001) and temperature ($p$ <0.0001) in their linear expressions were the factors that affected water absorption in OPCF. The mathematical model for this response variable showed an $R^2$ = 0.921, CV = 13.88 %, and F-value $p$ < 0.0001, with a significant lack-of-fit ($p$ = 0.2200). The following equation 2 shows the mathematical model used for the WAI.

$$WAI = 2.71 + 0.055 * T + 0.071 * t \ldots (2)$$

Figure 1A describes the WAI behavior in response to the effect of temperature and drying time. The highest water absorption occurred in samples dried at high temperatures and extended drying times, attributed to greater cellular damage in the samples causing a greater number of water molecules to bind to the polar chain residues (Meda & Ratti, 2005). Techeira *et al*. (2014), when characterizing flours from various cassava varieties, found that employing higher temperature conditions leads to an increase in WAI. They remark that this behavior is due to the presence of weaker intragranular forces, which allow the passage of water molecules into the starch granules, causing an increase in size. Cornejo and Rosell (2015) have specified that a high protein level also increases the water interaction. An increase in WAI is associated with the leaching and solubility of amylose and the loss of the crystalline starch structure. This behavior is similar to what was found in this study, where subjecting the flour to high-temperature conditions and extended drying times can affect the starch structure, resulting in similar behaviors. García-Pacheco *et al*. (2019) reported that the variation in WAI among different flours may be due to the relationship between variable protein concentrations, the degree of interaction with water, along with original characteristics they possess.

It has been demonstrated that WAI primarily depends on proteins and some of their parameters, such as size, shape, steric factors, and hydrophilic-hydrophobic balance of amino acids in molecules, as well as lipids and carbohydrates (Guerra-Baños *et al*., 2020). It is also noted that for low temperatures and drying times, the response showed minimum values. This can be explained by the higher moisture content in the samples which prevents the added amount

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of water from being absorbed in large quantities. Additionally, the low applied conditions did not affect the protein structure, reducing absorption. A low WAI may indicate that the starch is of low quality, as it tends to produce thin and unstable pastes. However, a very high WAI can negatively impact the mechanical properties of the dough (von Atzingen & Machado Pinto e Silva, 2005). The reference range for the WAI is between 0.82 and 15.52 g gel/g sample (Anderson, 1982).

**Table 2. Results of the regression analysis of second-order polynomial models for each of the response variables studied.**

| Parameters | Regression parameter coefficients | | | | | |
|---|---|---|---|---|---|---|
| | WAI | WSI | OAI | TPC | TAC | AoxA |
| Interception | -2.71 | -58.21 | -1.225 | -1905.38 | -416.44 | 11.19E5 |
| Lineal | | | | | | |
| DT | 0.055*** | 2.093*** | 0.089*** | 36.24** | NS | 2683.13** |
| Dt | 0.071*** | 4.046*** | -0.012** | NS | 31.08** | NS |
| Quadratic | | | | | | |
| DT x DT | NS | -0.012*** | -0.0008*** | NS | -0.0373** | NS |
| Dt x Dt | NS | -0.0770*** | NS | -2.498* | -0.3143** | NS |
| Interaction | | | | | | |
| Dt x Dt | NS | NS | NS | -1.457*** | -0.3443*** | -166.77*** |
| P-value for model | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $R^2$ | 0.92 | 0.97 | 0.71 | 0.85 | 0.90 | 0.85 |
| $R^2$adj | 0.90 | 0.94 | 0.60 | 0.74 | 0.83 | 0.79 |
| $R^2$pred | 0.86 | 0.86 | 0.17 | 0.32 | 0.64 | 0.72 |
| P-value for lack-of-fit | 0.2200 | 0.3200 | 0.2300 | 0.3400 | 0.5300 | 0.6500 |
| CV (%) | 13.88 | 2.84 | 12.05 | 12.19 | 6.68 | 8.39 |

NS = Not significant ($p$ > 0.1); *Significant at P < 0.1; **Significant at P < 0.05; ***Significant at P < 0.01. DT = Drying temperature; Dt = Drying time.

## Water Solubility Index

Time variable ($p$ < 0.001) and temperature ($p$ < 0.0001) in the linear expression were the factors with the most significant effect on the WSI response in the evaluated chicozapote flour. However, it is noticeable that the factors in the quadratic expressions and the interaction also showed significant effects on the response. The obtained model had an $R^2$ = 0.9700, CV = 2.84 %, and F-test $p$-value < 0.0001, without lack-of-fit with a p-value of 0.32.

Equation 3 represents the mathematical model used for WSI, in which a quadratic model is observed.

$$WSI = -58.207 + 2.093 * T + 4.046 * t - 0.019 * T * t - 0.0118 * T^2 - 0.076 * t^2 \ldots (3)$$

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In figure 1B, the WSI behavior in response to temperature and drying time is observed. It can be seen that as both drying times and temperatures increase, WSI also increases. García-Jimenez and Vázquez (2016) indicate that WSI is a directly proportional parameter to the amount of water-dissolved solids, which, in turn, is related to the degree of flour drying. This is a critical factor since a long drying time breaks the starch chains and generates short chains that retain a greater amount of water molecules. Njintang and Mbofung (2015) described that, while drying at high temperatures is more efficient, the process negatively impacts the product quality in terms of color, functionality, and flour performance during reconstitution. Techeira *et al*. (2014) obtained a similar behavior in cassava flour. The highest solubility values were obtained in the highest temperature range as they exhibit a weaker intragranular structure, which breaks more easily under these conditions, allowing the exudation of more molecular components into the dispersion.

## Oil Absorption Index

In Figure 1C, the behavior of OAI of the OPCF concerning temperature and drying times is illustrated. The factors showing the most significant effect on the response were temperature and time in its linear expression. The model for this response variable showed an $R^2$ = 0.7115, CV = 12.05 %, and F-test p-value = 0.0084, without lack-of-fit with a p-value of 0.23. Equation 4 represents the mathematical model used for the water solubility index, in which a quadratic model is observed.

$$OAI = -1.225 + 0.088 * T - 0.018 * t - 7.989X10^{-4} * T^2 \ldots (4)$$

It is observed that as the temperature values increase, the response is better, increasing the OAI until reaching a maximum. Punia-Bangar *et al*. (2022) mention that the fruit has large amounts of proteins, so this response is explained by the findings reported by Miquilena *et al*. (2016), who mentions that OAI is the ability of flour proteins to physically bind to fat through capillary attraction. This occurs under moderate conditions within a certain range of temperatures and drying times for flours, where the protein structure seems to undergo small structural alterations that favor the physical fat retention. This could be a result of the physical entrapment of fats by proteins through the formation of micelles, leading to an increase in the response, similar to the results of the present study. However, when the values of temperature and drying time conditions continue to increase, the proteins begin to lose structure, subsequently leading to a decrease in the response.

The OAI is attributed to the physical entrapment of fat within proteins, where non-covalent bonds such as electrostatic forces, hydrophobic interactions, and hydrogen bonds play a key role in lipid-protein interaction (Lawal, 2004). This property is crucial for formulating bakery products, meat products and substitutes, soups, and frying foods, as it is related to the flavor retention capacity and the smoothness of the end product (El-Adawy & Taha, 2001). Additionally, OAI reduces the development of oxidative rancidity, thereby increasing stability over storage (Shate, 2002).

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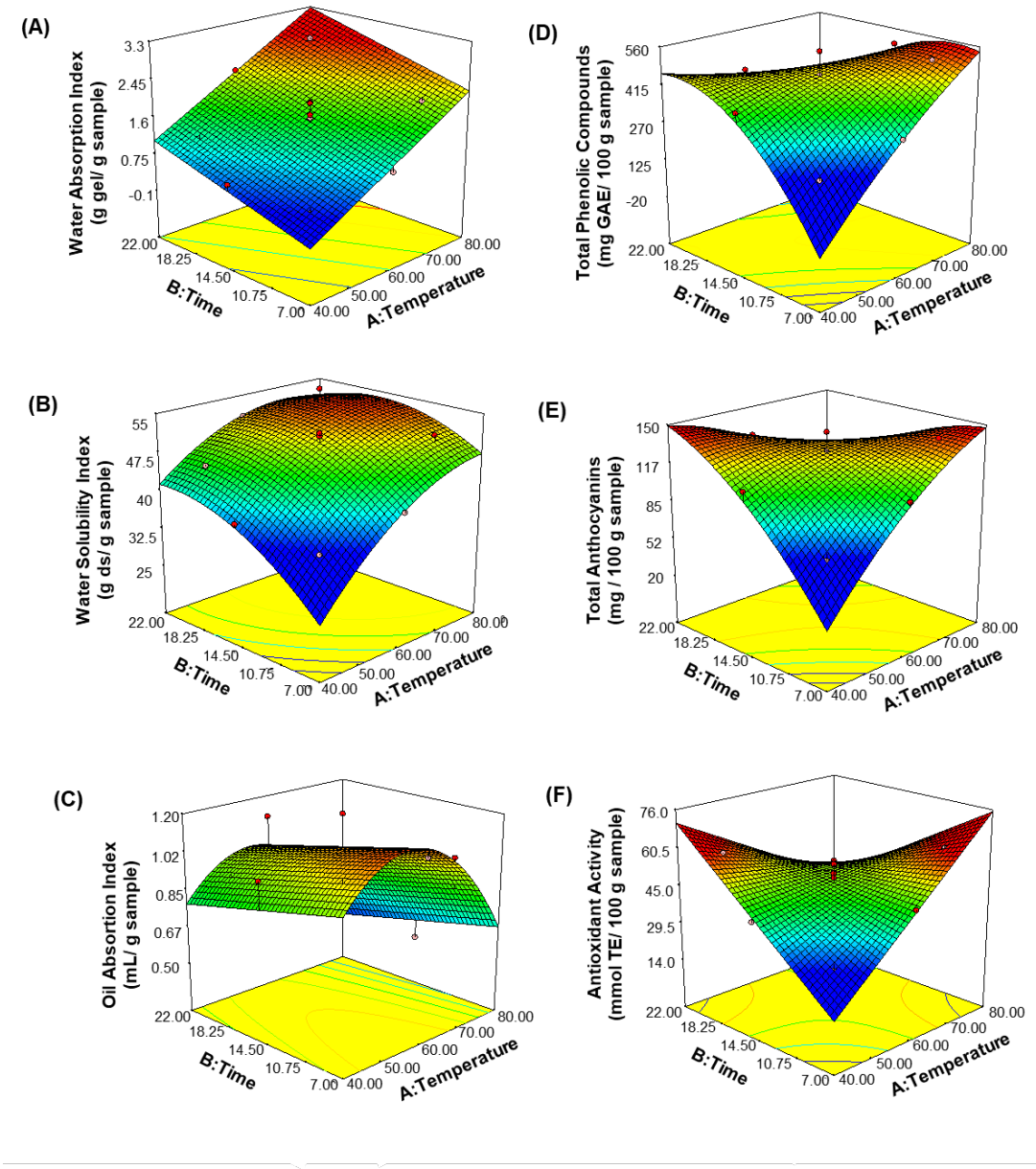


**Figure 1. Contour plots showing the effect of the drying process variables (temperature and time) on the response variables (A) Water Absorption Index, (B) Water Solubility Index, (C) Oil Absorption Index, (D) Total Phenolic Compounds, (D) Total Anthocyanins, and (F) Antioxidant Activity of processed chicozapote flour.**

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### Total Phenolic Content

In this study, it was found that temperature ($p$ = 0.049) was the factor showing the most significant effect on the TPC in its linear expression. Additionally, the temperature and time factors in its quadratic expression also showed a significant effect on the response. The model for this response variable exhibited an $R^2$ = 0.8500, CV = 12.19 %, and F-test p-value < 0.0084. Equation 5 represents the mathematical model used for determining the total phenolic content:

$$TPC = -1905.38 + 36.24 * T - 1.46 * T * t - 0.10 * T^2 - 2.49 * t^2 \ldots(5)$$

Figure 1D shows the behavior of TPC under the influence of varying temperatures and drying time. It can be observed that under high temperatures and short drying times, the TPC is favored. Gómez-Maqueo *et al*. (2020) reported that the content of phenolic compounds and carotenoids in tomatoes remains stable during processing at high temperatures. Furthermore, they also reported that the thermal process can increase the content of phenolic compounds by releasing phenolic acids bound to cell constituents. Similarly, Kim and Chin (2016) observed a similar behavior in the drying process in the range of 60 and 70 ºC, attributing this effect to Maillard reactions occurring during toasting. Yao *et al*. (2020) reported an increase in TPC with increasing temperature due to the destruction of covalent bonds and cellular constituents, releasing antioxidants, such as phenolic acids, flavones, phenols, and other compounds, which are bound to macromolecules produced by heat treatment. Thus, it can be concluded that the effect of heat treatment on the content of phenolic compounds depends on the species and variety of the raw material used. These variations also depend on the chosen method for extracting phenolic compounds as well as the temperature and processing time.

### Total Anthocyanin Content

In Figure 1E, it can be observed that the factors with a significant effect on anthocyanins were the time variable in its linear term ($p$ = 0.0446) and in its quadratic term ($p$ = 0.0223), as well as the temperature variable ($p$ = 0.043) in its quadratic term and the interaction between these factors with $p$ = 0.0003. The mathematical model for this response variable showed values of $R^2$ = 0.9040, CV = 6.68 %, and F-test p-value < 0.0019, with a significant adjustment probability ($p$ = 0.5315). Equation 6 presents the mathematical model used for the TAC determination.

$$TAC = -416.44 + 9.92 * T + 31.08 * t - 0.34 * T * t - 0.037 * T^2 - 0.314 * t^2 \ldots 6$$

It can be observed that the TAC increased as temperature increased. Menchaca-Armenta *et al*. (2020) reported higher levels of anthocyanin at intermediate-high temperatures (85 to 105 °C), similar to the observations in this study. Yemmireddy *et al*. (2013) propose that the effect of temperature on anthocyanins is a hydrolysis of the glycosidic bond, followed by a conversion from aglycone to chalcone (colorless pigments). It should be noted that temperatures exceeding 100 ºC result in much greater color degradation than temperatures below 90 ºC, since temperature can induce an increase in the content of negative transcription factors, thus binding to promoters

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and inhibiting the expression of anthocyanin genes Zou *et al*. (2021). The stability of anthocyanins in foods is significantly affected by temperature.

In general, the structural characteristics that lead to an increase in pH stability also contribute to thermal stability. Highly hydrolyzed anthocyanins are less stable than methylated, glucosylated, or acetylated forms (Habibi *et al.*, 2020a). The thermal stability of anthocyanins varies with their structure, pH, oxygen presence, and interactions with other components in the system (Habibi *et al*., 2020b). Wang and Xu (2007) specify that anthocyanins are unstable when exposed to high temperatures.

### Antioxidant Activity (AoxA)

In Figure 1F, it is observed that the factors that had a significant effect on AoxA were the temperature variable and drying time variable in its linear terms, as well as the interaction between both factors with $p$ = 0.002. The mathematical model for this response variable showed values of $R^2$ = 0.8417, CV = 8.39 %, and F-test p-value = 0.0006, with a significant adjustment probability (p=0.648). Equation 7 represents the mathematical model used for the AoxA by the ABTS method of dried chicozapote fruit:

$$AoxA = -1.189E05 + 2683.13 * T + 10409.53 * t - 166.77 * T * t \ldots (7)$$

The parameters that showed the greatest effect on AoxA were drying time and temperature in their linear expression. It can be observed that at high temperatures and low drying times, the response increases. Alvis-Celis (2020) explains that the increase in AoxA could result from high temperatures allowing the formation of new compounds with higher antioxidant activity, such as those formed in the Maillard reaction. Giovanelli *et al.* (2001) reported that heat treatment increases the level of free flavonols, which have significant antioxidant activity. Krzykowski *et al*. (2020) state that heating is the main cause of the loss of antioxidants, but it can also induce the formation of compounds such as melanoidins through the Maillard reaction, and these compounds have antioxidant effects. These compounds are generated at high temperatures, such as 100 °C, and short drying time.

Zapata Bustamante *et al*. (2014) reported a similar behavior as in the present study when increasing the temperature during the roasting of cocoa beans. They mentioned that this occurs due to the generation of intermediate products and melanoidins caused by the Maillard reaction, as the radical-scavenging activity increases due to the presence of melanoidins. However, it is possible to observe that as the temperature continues to increase, there is a diminishing trend, which may be attributed to the formation of other compounds with lower antioxidant activity during the Maillard reaction at higher temperatures. Piga *et al*. (2003) subjected “Presidente” plum cultivars to drying using two temperatures (60 and 85 °C) and observed that the AoxA doubled at 85°C. Similar results were found in the response to this project. They explain that the increase in AoxA could be the result of two factors: a) partial oxidation of phenolic compounds increases the antioxidant power present in the sample (temporarily), b) high temperature allows the formation of new compounds with greater antioxidant capacity, such as those formed in the Maillard reaction.

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## Optimization

The optimization process was carried out to determine the best temperature and drying time conditions, aiming to obtain dehydrated flour with good techno-functional and nutraceutical properties. A numerical method was employed for this procedure, and different criteria were established for each of the response variables. High values are expected for the responses of total phenolic content, total anthocyanin content, antioxidant activity, water absorption index, and water solubility index. In contrast, low values are desired for the oil absorption index. These variables were chosen for optimization as the development of a food product with good characteristics and health benefits depends on its functional and nutraceutical properties.

In Figure 2, the bar graphs of individual desirability for the response variables and the overall or combined desirability of the process are shown. The maximum desirability has a value of 1, and the minimum desirability has a value of 0. It can be observed that the individual desirability for both temperature and drying time was 1.0, as they were assigned a range as their target, indicating that they will always have a desirability of 1.

The AoxA showed a desirability of 0.881, indicating that it achieved approximately 88.1 % of the difference from the upper limit to the lower limit of AoxA. The TAC showed a desirability of 0.887, exhibiting that it covered approximately 88.7 % of the difference from the upper limit to the lower limit. TPC presented a desirability of 0.918, indicating that it reached 91.8 % of the difference from the upper limit to the lower limit of TPC. In the case of OAI, it showed a desirability of 0.541, indicating that it covered approximately 54.1 % of the difference from the upper limit to the lower limit of OAI. The WSI showed a desirability of 0.872, indicating that it reached approximately 87.2 % of the difference from the upper limit to the lower limit of WSI. The WAI presented a desirability of 0.784, indicating that it reached approximately 78.4 % of the difference from the upper limit to the lower limit of WAI.

Global desirability (GD) or combined is presented by the following equation 8:

$$GD = (0.881 * 0.887 * 0.918 * 0.541 * 0.784 * 0.802)^{\frac{1}{6}} = DG = 0.802 \ldots (8)$$

With the obtained results from numerical optimization, the best process conditions were determined to be DT of 74 ºC and Dt of 12 hours. Under these optimal conditions, the following predicted values were obtained for each of the mathematical models: OAI= 0.82 mL of oil absorbed/g of flour, WAI= 2.24 g gel / g (d.b.), WAI=52.27 g gel / g (d.b.), AoxA = 56.57 mmol TE/ 100 g (d.b.), TAC= 134.36 mg/100 g (d.b.), TPC= 514.58 mg GAE/100 g (d.b.).

For the validation of the employed models, chicozapote fruit was dehydrated under the optimal conditions found in the process. After obtaining the dehydrated fruit, flour was produced and evaluated to verify the predicted values.

From the characterization of the OPCF the following average values and standard

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deviations were obtained: OAI= 0.7 ± 0.25 mL of oil absorbed / g of flour, WAI= 2.259 ± 0.38 g gel / g (d.b.), WSI = 49.90 ± 0.30 g dry solids / g original solids, AoxA = 64.42 mmol TE/ 100 g (d.b.), TAC= 131.07 mg/100 g (d.b.), TPC = 587.77 mg GAE/100 g (d.b.). When the experimental values were compared against the values predicted by the mathematical models, no significant difference was observed between them ($p < 0.05$). Therefore, the employed model was demonstrated experimentally to have a good fit for finding the optimal temperature and drying time conditions for obtaining dehydrated fruit with good techno-functional and nutraceutical properties.

## Characterization of optimized processed chicozapote flour

### Techno-functional properties

To extend the shelf life of the fruit, its techno-functional properties were modified through the optimization of the drying process, obtaining a functional and nutraceutical flour to promote its use as an ingredient in the development of new foods as a way of valorizing the crop. The techno-functional properties evaluated were WAI, WSI, and OAI. The fresh fruit showed low values of WAI and OAI (0.001 ± 0.00 g gel/g and 0.000 ± 0.00 mL of oil absorbed/g, respectively); which was expected due to its high water content (88.02 %). On the other hand, for the OPCF, WAI values of 2.259 ± 0.38 g water/g were observed. This property can be influenced by several factors; one is the chemical composition of the flour. Martínez-Martí *et al.* (2023) investigated the water absorption index of clementine peel dried by hot air, reporting values of 6.6 g water/g. The lower WAI values observed in this study could be due to the different environmental conditions where the products were developed, as well as the chemical composition of each material. The OAI (0.7 ± 0.25 mL of oil absorbed/g) obtained for the OPCF in this study is lower than that reported for functional corn flour with cowpea obtained by extrusion (Sotelo-Díaz *et al*., 2023). A lower OAI would ensure that if the product is fried or comes into contact with oil, it will absorb less oil. This makes OPCF a good option for making fried foods. The WSI determined for fresh and processed samples was 20.12 ± 0.75 g dry solids/100 g original solids and 49.90 ± 0.30 g dry solids/100 g original solids, respectively. The observed WSI values for OPCF suggest that it can be used for functional beverage production.

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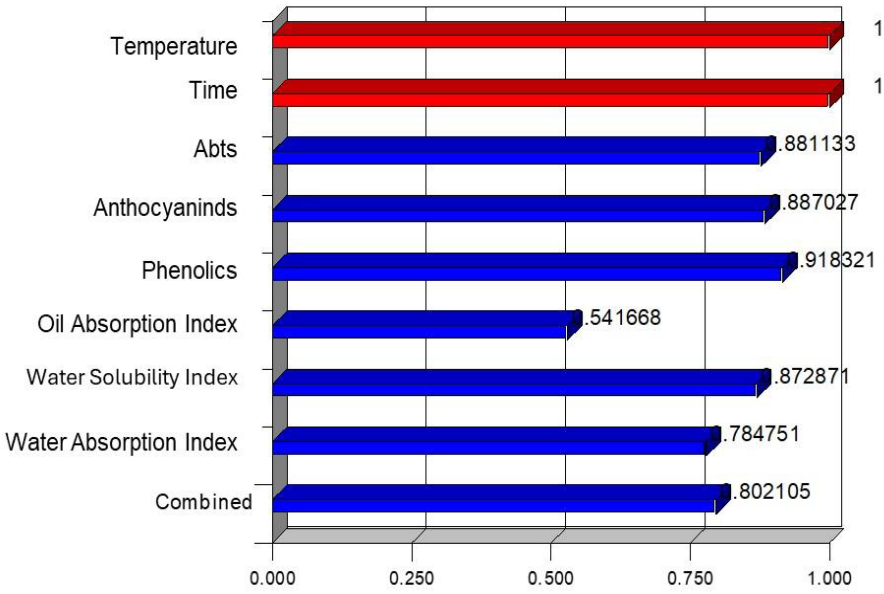


**Figure 2. Individual and global (combined) desirability of the process variables (temperature and time) and responses (water absorption index, water solubility index, oil absorption index, total phenolic compounds, total anthocyanins, and antioxidant activity) were analyzed during optimization.**

## Nutraceutical properties

In Figure 3A, the TPC of the OPCF, prepared with the best drying process conditions (DT= 74.1 °C / Dt = 12 h), is shown. The TPC of the optimized flour was significantly lower ($p<0.05$) than the unprocessed chicozapote flour (UPCF) [587.77 vs 691.28 mg GAE/100 g (d.b.); retention= 85.03 %]. Similar behaviors have been reported in microalgae (retention = 50 %) and mango (retention= 47 %) by researchers such as Subbiah *et al*. (2023) and Medeiros *et al*. (2022), who attribute such decrease to the degradation of phenolic compounds due to prolonged exposure to high temperature. However, despite the observed TPC decrement of the optimized flour, the values in this study are similar to those reported by Baky *et al*. (2022) for a fruit from the same family as chicozapote (*Manilkara hexandra* = 650 mg GAE/100 g) extracted with a hydroalcoholic solution and without processing.

The TAC of OPCF was significantly lower ($p<0.05$) than the UPCF [131.67 vs 539.07 mg/100 g (d.b.); retention = 24.43 %] (Figure 3B). The low retention values of TAC are due to the drastic effect of the drying process; temperatures above 60 °C may cause the denaturation of anthocyanins (Patras *et al*., 2010). The values observed in this study for UPCF are similar to

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those obtained by Li *et al*. (2023) for fresh red radish (608.91 mg/100 g), but higher than those of red radish dried with hot air at 60 °C (52.97 mg/100 g) (retention = 9 %). This suggests that the anthocyanin type in chicozapote is more resistant to temperature, or the matrix in which they are found partially protects them from degradation.

The AoxA of the UPCF and OPCF was determined using the ABTS colorimetric technique (Figure 3C). The values obtained for the analyzed samples were 38.86 y 64.42 mmol ET/100 g (d.s.) for UPCF and OPCF, respectively [increase = 65.75 %]. Despite the notable decrease in the content of phytochemicals to which various authors have attributed AoxA (Li *et al*., 2023; Patras *et al*., 2010; Quintero-Soto *et al*., 2018; Xu & Chang, 2007), this study observed a 1.6-fold increase in this activity. These values are higher than those reported by Jiménez-Ortega *et al*. (2024) for 10 antioxidant supplements. This indicates that OPCF could be a good option to be used as a dietary supplement.

This behavior could be explained by the fact that during the drying process, temperatures are applied that trigger a large number of reactions in the matrix undergoing processing. One of the reactions with a significant impact is the Maillard reaction, where free amino acids present in the food react with available reducing sugars, forming compounds that give certain brown tones to the fruit (Félix-Medina *et al*., 2021). These compounds are known as melanoidins, which have been reported to generate AoxA (Quintero-Soto *et al*., 2022). These compounds, together with phytochemicals, could be acting synergistically to increase the antioxidant activity of OPCF. However, further studies are required to confirm this effect.

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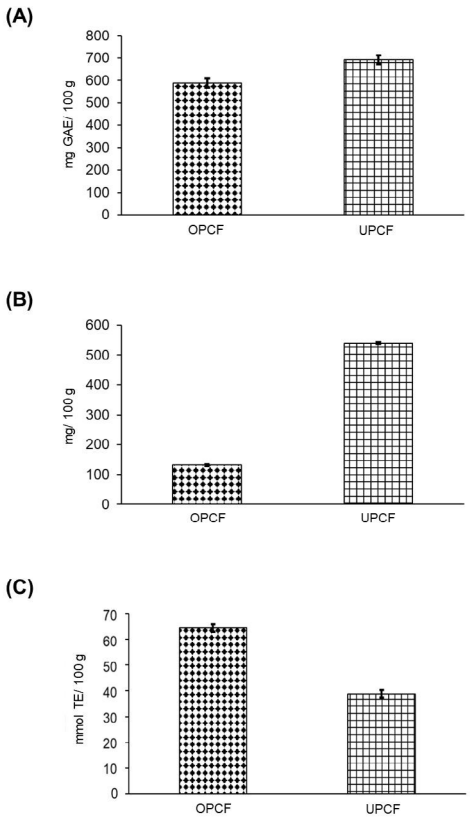


**Figure 3. Content of phenolic compounds (A), anthocyanins (B), and antioxidant activity (C) of an optimized processed chicozapote flour (OPCF) and unprocessed chicozapote flour (UPCF).**

## Conclusions

The predictive mathematical models obtained for the response variables analyzed in this study were adequate, as they showed values of $R^2 \geq 0.71$, F p-value ≤ 0.001, CV ≤ 13 %, and did not show a lack-of-fit. The optimal conditions found (DT: 74°C and DT: 12 h) were useful for producing a dehydrated chicozapote flour with good techno-functional properties (water absorption and solubility capacity) and nutraceutical properties (total phenolic compounds, total anthocyanins, and antioxidant activity). The retention percentages of total phenolic compounds (85.03 %) and the increase in antioxidant activity (65.75 %) after the optimized drying process of chicozapote suggest that the optimal conditions obtained are suitable for carrying out the dehydration process of the fruit, thereby extending its shelf life while largely preserving its nutraceutical capacities.

## Authors' contribution

Work conceptualization: MFQS, MEVO, and GDRH. Methodology development: EMCM, CNBM, IDP, and JVFM, Software management: MFQS and MEVO. Experimental validation: FSL and ODAL. Analysis of results: EMCM, MFQS, and MEVO. Manuscript writing and preparation: EMCM. Drafting, revising, and editing: MEVO and MFQS. Project management: MEVO.

All authors of this manuscript have read and accepted the submitted version.

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## Declaration of interest

The authors declare that there are no conflicts of interest.

## References

Abdel-Aal, E. S. M., & Hucl, P. (1999). A Rapid Method for Quantifying Total Anthocyanins in Blue Aleurone and Purple Pericarp Wheats. *Cereal Chemistry*, *76*(3), 350-354. https://doi.org/10.1094/CCHEM.1999.76.3.350

Alvis-Celis, R. (2020). Efecto de temperatura y velocidad de secado en la actividad antioxidante de la mashua (*Tropaeolum tuberosum*) en el secado en bandejas. *Revista Científica UNTRM: Ciencias Naturales e Ingeniería*, *3*(1), 16-21. https://doi.org/https://doi.org/10.25127/ucni.v3i1.587

Anderson, R. (1982). Water absortion and solubility and amilograph characteristics f roll cooked small grain products. *Cereal Chemistry*, *59*, 265-269. https://www.cerealsgrains.org/publications/cc/backissues/1982/Documents/CC1982a68.html

Baky, M. H., Kamal, A. M., Haggag, E. G., & Elgindi, M. R. (2022). Flavonoids from Manilkara hexandra and antimicrobial and antioxidant activities. *Biochemical Systematics and Ecology*, *100*, 104375. https://doi.org/10.1016/j.bse.2021.104375

Bashir, S. (2019). Pharmacological importance of Manilkara zapota and its bioactive constituents. *Boletín Latinoamericano y del Caribe de Plantas Medicinales y Aromáticas*, *18*(4), 347–358.

https://doi.org/Https://doi.org/10.35588/blacpma.19.18.4.22

Cornejo, F., & Rosell, M. C. (2015). Physicochemical properties of long rice grain varieties in relation to gluten free bread quality. *LWT - Food Science and Technology*, *62*(2), 1203-1210. https://doi.org/10.1016/j.lwt.2015.01.050

El-Adawy, T. A., & Taha, K. M. (2001). Characteristics and composition of different seed oils and flours. *Food Chemistry*, *74*(1), 47-54. https://doi.org/https://doi.org/10.1016/S0308-8146(00)00337-X

Espinoza-Moreno, R. J., Reyes-Moreno, C., Gutiérrez-Dorado, R., Milán-Carrillo, J., Cuevas-Rodríguez, E. O., Mora-Rochín, S., . . . Perales-Sánchez, J. X. K. (2021). Alimento funcional para adultos mayores producido por extrusión a partir de granos integrales de maíz/frijol común. *Acta Universitaria*, *31*, 1-18. https://doi.org/10.15174/au.2021.3217

Food and Agriculture Organization of the United Nations [FAO]. (2013). *Food and Agriculture Organization of the United Nations*. Retrieved January 2024 from http://faostat.fao.org/site/636/DesktopDefault.aspx?PageID=636#ancor

Félix-Medina, J. V., Gutiérrez-Dorado, R., López-Valenzuela, J. A., López-Ángulo, G., Quintero-Soto, M. F., Perales-Sánchez, J. X. K., & Montes-Ávila, J. (2021). Nutritional, antioxidant and phytochemical characterization of healthy ready-to-eat expanded snack produced from maize/common bean mixture by extrusion. *LWT - Food Science and Technology*, *142*, 111053. https://doi.org/10.1016/j.lwt.2021.111053

García-Cuevas, X., Rodríguez-Santiago, B., & Parraguirre-Lezama, C. (2021). Notas Importates Sobre el Chicozapote (*Manilkara zapata* L. *Van Royen*). *Revista Mexicana de Ciencias Forestales*, *18*(74), 45-63. https://cienciasforestales.inifap.gob.mx/index.php/forestales/article/view/1048

García-Jimenez, A., & Vázquez , L. (2016). Masa y harina de maíz nixtamalizado. *Investigacion y Desarrollo en Ciencia y Tecnología de Alimentos*, *1*(2), 78-82. http://www.fcb.uanl.mx/IDCyTA/files/volume1/2/1/15.pdf

García-Pacheco, Y., Cabrera-Mercado, D., Ballestas-Santos, J. A., & Campo-Arrieta, M. J. (2019). Efecto de diferentes tratamientos térmicos sobre las propiedades tecfuncionales de la harina de fríjol blanco (*Phaseolus lunatus* L.) y la determinación de su potencial uso agroalimentario. *INGE CUC*, *15*(2), 132-142. https://doi.org/https://doi.org/10.17981/ingecuc.15.2.2019.13

Giovanelli, G., Zanoni, B., Lavelli, V., & Nani, R. (2001). Water sorsión, drying and antioxidant properties of dried tomato products. *Journal of Food Engineering*, *52*(2), 135-141. https://doi.org/10.1016/S0260-8774(01)00095-4

Gómez-Maqueo, A., Escobedo-Avellaneda, Z., & Welti-Chanes, J. (2020). Phenolic Compounds in Mesoamerican Fruits—Characterization, Health Potential and Processing with Innovative Technologies. *International Journal of Molecular Sciences*, *21*(21). https://doi.org/10.3390/ijms21218357

Guerra-Baños, E. C., Baños Dorantes, M. I., Luna-Jiménez, A. L., González-Cortés, N., & Jiménez-Vera, R. (2020). Caracterización de Harina de Naranja (*Citrus x sinensis)* para Uso Alimentario. *European Scientific Journal*, *16*(6), 1857. https://doi.org/10.19044/esj.2020.v16n6p1

Habibi, F., Ramezanian, A., Guillén, F., Castillo, S., Serrano, M., & Valero, D. (2020a). Changes in Bioactive Compounds, Antioxidant Activity, and Nutritional Quality of Blood Orange Cultivars

at Different Storage Temperatures. *Antioxidants*, *9*(10), 1016. https://doi.org/10.3390/antiox9101016

Habibi, F., Ramezanian, A., Guillén, F., Serrano, M., & Valero, D. (2020b). Blood oranges maintain bioactive compounds and nutritional quality by postharvest treatments with γ-aminobutyric acid, methyl jasmonate or methyl salicylate during cold storage. *Food Chemistry*, *306*, 125634. https://doi.org/10.1016/j.foodchem.2019.125634

Jiménez-Ortega, L. A., López-Romero, B. J., Heredia-Batiz, J. M., Bastidas-Bastidas, P. J., & Heredia, J. B. (2024). These values are higher than those reported by Jiménez-Ortega et al. (2024) for 10 antioxidant supplements. This indicates that OPCF could be a good option to be used as a dietary supplement. *Revista Bio Ciencias*, *11*, e1585. https://doi.org/10.15741/revbio.11.e1585

Kim, H. S., & Chin, K. B. (2016). Effects of Drying Temperature on Antioxidant Activities of Tomato Powder and Storage Stability of Pork Patties. *Korean Journal for Food Science of Animal Resources*, *36*, 51 - 60. https://doi.org/https://doi.org/10.5851/kosfa.2016.36.1.51

Krzykowski, A., Dziki, D., Rudy, S., Gawlik-Dziki, U., Janiszewska-Turak, E., & Biernacka, B. (2020). Wild Strawberry Fragaria vesca L.: Kinetics of Fruit Drying and Quality Characteristics of the Dried Fruits. *Processes*, *8*(10). https://doi.org/10.3390/pr8101265

Lawal, O. S. (2004). Functionality of african locust bean (Parkiabi globossa) protein isolate: effects of pH, ionic strength and various protein concentrations. *Food Chemistry*, *86*(3), 345-355. https://doi.org/10.1016/j.foodchem.2003.09.036

Li, W., Zhang, Y., Deng, H., Fan, X., Yang, H., & Tan, S. (2023). In vitro and in vivo bioaccessibility, antioxidant activity, and color of red radish anthocyanins as influenced by different drying methods. *Food Chemistry*, *18*, 100633. https://doi.org/10.1016/j.fochx.2023.100633

Martínez-Martí, J., Panušková, K., Larrea, V., Bleha, R., Quiles, A., & Hernando, I. (2023). Using different physical treatments to modify the structure and improve the technofunctional properties of clementine by-products. *Food Structure*, *38*, 100346. https://doi.org/10.1016/j.foostr.2023.100346

Meda, L., & Ratti, C. (2005). Rehydration of freeze-dried strawberries at varying temperatures. *Journal of Food Process Engineering*, *28*(3), 233-246. https://doi.org/10.1111/j.1745-4530.2005.00404.x

Medeiros, R., Da Silva Junior, E., Barros, Z., Da Silva, J., Brandao , S., & Azoubel, P. (2022). Convective drying of mango enriched with phenolic compounds from grape residue flour under different impregnation methods. *Food Research International*, *158*, 111539. https://doi.org/10.1016/j.foodres.2022.111539

Menchaca-Armenta, M., Ramírez-Wong, B., Torres-Chávez, P. I., Quintero-Ramos, A., Ledesma-Osuna, A. I., Frutos, M. J., . . . Morales-Rosas, I. (2020). Effect of extrusion conditions on the anthocyanin content, functionality, and pasting properties of obtained nixtamalized blue corn flour (Zea mays L.) and process optimization. *Journal of Food Science*, *85*(7), 2143-2152. https://doi.org/10.1111/1750-3841.15312

Miquilena, E., Higuera, A., & Rodríguez, B. (2016). Evaluación de propiedades funcionales de cuatro harinas de semillas de leguminosas comestibles cultivadas en Venezuela. *Revista de la Facultad de Agronomía*, *33*(1), 58-75. https://produccioncientificaluz.org/index.php/agronomia/article/view/27193

Njintang , Y. N., & Mbofung, C. M. F. (2015). *Quinoa: Improvement and Sustainable Production*.

Jhon Wiley y Sons Inc.

Patras, A., Brunton, N. P., O Donnell, C., & Tiwari, B. K. (2010). Effect of thermal processing on anthocyanin stability in foods; mechanisms and kinetics of degradation. *Trends in Food Science and Technology*, *21*(1), 3-11. https://doi.org/10.1016/j.tifs.2009.07.004

Piga, A., Del Caro, A., & Corda, G. (2003). From plums to prunes: influence of drying parameters on polyphenols and antioxidant activity. *Journal of Agricultural and Food Chemistry*, *51*(12), 3675-3681. https://doi.org/10.1021/jf021207

Punia-Bangar, S., Sharma, N., Kaur, H., Kaur, M., Sandhu, K. S., Maqsood, S., & Ozogul, F. (2022). A review of Sapodilla (*Manilkara zapota*) in human nutrition, health, and industrial applications. *Trends in Food Science & Technology*, *127*, 319-334. https://doi.org/https://doi.org/10.1016/j.tifs.2022.05.016

Quintero-Soto, M. F., Espinoza-Moreno, R. J., Félix-Medina, J. V., Salas-López, F., López-Carrera, C. F., Argüelles-López, O. D., . . . Gómez-Favela, M. A. (2022). Comparison of Phytochemical Profile and In Vitro Bioactivity of Beverages Based on the Unprocessed and Extruded Sesame (*Sesamum indicum* L.) Seed Byproduct. *Foods*, *11*(20). https://doi.org/10.3390/foods11203175

Quintero-Soto, M. F., Saracho-Peña, A. G., Chavez-Ontiveros, J., Garzon-Tiznado, J. A., Pineda-Hidalgo, K. V., Delgado-Vargas, F., & López-Valenzuela , J. A. (2018). Phenolic profiles and their contribution to the antioxidant activity of selected chickpea genotypes from Mexico and ICRISAT collections. *Plant Foods for Human Nutrition*, 122-129. https://doi.org/10.1007/s11130-018-0661-6

Rivas-Gastelum, M. F., Garcia-Amezquita, L. E., Garcia-Varela, R., & Sánchez-López, A. L. (2023). *Manilkara zapota* “chicozapote” as a fruit source of health-beneficial bioactive compounds and its effects on chronic degenerative and infectious diseases, a review. *Frontiers in nutrition*, *10*, 1194283. https://doi.org/10.3389/fnut.2023.1194283

Ruiz-Armenta, X. A., Ruiz-Armenta, J. E., Espinoza-Moreno, R. J., Gutiérrez-Dorado, R., Aguilar-Palazuelos, E., Zazueta-Morales, J. d. J., & Gómez-Favela, M. A. (2022). Aprovechamiento de subproducto de sésamo y extrusión optimizada para obtención de harina funcional con propiedades tecno-funcionales, nutricionales y antioxidante mejoradas. *Acta Universitaria*, *32*, 1-20. https://doi.org/10.15174/au.2022.3494

Serna-Cock, L., Torres-Leon, C., & Ayala-Aponente, 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

Shate, S. K. (2002). Dry bean protein functionality. *Critical Reviews in Biotechnology*, *22*(2), 175-223. https://doi.org/10.1080/07388550290789487

Servicio de Información Agroalimentaria y Pesquera [SIAP]. (2024). *Anuario Estadístico de la Producción Agrícola. Cierre Agrícola 1980-2018.* . Retrieved December from https://nube.siap.gob.mx/cierreagricola/

Singleton, V. L., Orthofer, R., & Lamuela-Raventós, R. M. (1999). Analysis of Total Phenols and Other Oxidation Substrates and Antioxidants by Means of Folin-Ciocalteu Reagent. *Methods in Enzymology*, *299*, 152-178. https://doi.org/10.1016/S0076-6879(99)99017-1

Sotelo-Díaz, L. I., Igual, M., Martínez-Monzó, J., & García-Segovia, P. (2023). Techno-Functional Properties of Corn Flour with Cowpea (Vigna unguilata) Powders Obtained by Extrusion. *Foods*, *12*(2), 298. https://doi.org/10.3390/foods12020298

Subbiah, V., Duan, X., Agar, O. T., Dunshea, F. R., Barrow, C. J., & Suleria, H. A. R. (2023). Comparative study on the effect of different dryng techniques on phenolic compounds in Australian beach-cast brown seaweeds. *Algal Research*, *72*(1), 103140. https://doi.org/10.1016/j.algal.2023.103140

Techeira, N., Sívoli, L., Perdomo, B., Ramírez, A., & Sosa, F. (2014). Caracterización físicoquímica, funcional y nutricional de harinas crudas obtenidas a partir de diferentes variedades de yuca (*Manihot esculenta* Crantz), batata (*Ipomoea batatas* Lam) y ñame (*Dioscorea alata*), cultivadas en Venezuela. *Interciencia*, *39*(3), 191-197. https://www.redalyc.org/articulo.oa?id=33930206009 (IN FILE)

Vargas y Vargas, M. d. L., Sauri Duch, E., Tamayo Canul, E., González Novelo, S. A., & Tamayo Cortez, J. (2015). Chicozapote fresco y cortado (*Achras Sapota*) con actividad antioxidante; una demanda actual del consumo de frutas. *Revista Mexicana de Agronegocios*, *36*(19), 1315-1324. https://www.redalyc.org/pdf/141/14132408017.pdf

von Atzingen, M. C., & Machado Pinto e Silva, M. E. (2005). Evaluación de la textura y color de almidones y harinas en preparaciones sin gluten. *Ciencia y Tecnologia Alimentaria*, *4*(5), 319-323. https://doi.org/10.1080/11358120509487658

Wang, W.-D., & Xu, S.-Y. (2007). Degradation kinetics of anthocyanins in blackberry juice and concentrate. *Journal of Food Engineering*, *82*(3), 271-275. https://doi.org/10.1016/j.jfoodeng.2007.01.018

Xu, B., & Chang, S. (2007). A comparative study on phenolic profiles and antioxidant activities of legumes as affected by extraction solvents. *Journal of Food Science*, 159-166. https://doi.org/10.1111/j.1750-3841.2006.00260.x

Yao, L., Fan, L., & Duan, Z. (2020). Effect of different pretreatments followed by hot-air and far-infrared drying on the bioactive compounds, physicochemical property and microstructure of mango slices. *Food Chemistry*, *305*, 125477. https://doi.org/https://doi.org/10.1016/j.foodchem.2019.125477

Yemmireddy, V. K., Chinnan, M. S., Kerr, W. L., & Hung, Y.-C. (2013). Effect of drying method on drying time and physico-chemical properties of dried rabbiteye blueberries. *LWT-Food Science and Technology*, *50*(1), 739-745. https://doi.org/10.1016/j.lwt.2012.07.011

Zapata- Bustamante, S., Tamayo-Tenorio, A., & Rojano, B. (2014). Efecto del Tostado Sobre los Metabolitos Secundarios y la Actividad Antioxidante de Clones de Cacao Colombiano: Effect of Roasting on the Secondary Metabolites and Antioxidant Activity of Colombian Cocoa Clones. *Revista Facultad Nacional de Agronomía*, *68*, 7497-7507. https://doi.org/10.15446/rfnam.v68n1.47836

Zou, C., Huang, L., Li, D., Ma, Y., Liu, Y., Wang, Y., . . . Sun, L. (2021). Assembling cyanidin-3-O-glucoside by using low-viscosity alginate to improve its in vitro bioaccessibility and in vivo bioavailability. *Food Chemistry*, *355*, 129681. https://doi.org/https://doi.org/10.1016/j.foodchem.2021.129681