Food Biophysics (2025) 20:11
https://doi.org/10.1007/s11483-024-09892-0

RESEARCH

Exploring the Potential of Spray-Dried Blackberry Powder Enriched with Zinc and Folic Acid as a Nutritional Alternative for Children and Pregnant Women

Oscar Vega-Castro[1,2] · Vargas-Marulanda Diego[1,2] · Castro-Tobón Santiago[1,2] · Vallejo-Marulanda Laura[2] · Vanegas-Arboleda Valentina[2] · Henao-González Daniel[2] · Gómez-Narváez Faver[2]

Received: 1 April 2024 / Accepted: 8 October 2024

Abstract

Currently, strategies to achieve the Sustainable Development Goals (SDGs) are being sought worldwide. Accordingly, this study seeks to contribute to achieving SDGs 2 (Zero Hunger) and 3 (Good Health and Well-being) by addressing nutritional deficiencies in pregnant women and children. These vulnerable populations worldwide have malnutrition problems associated with a lack of zinc and folic acid, causing them health problems. This research aimed to develop a blackberry powder fortified with zinc and folic acid obtained by spray drying as a nutritional alternative for children and pregnant women. The blackberry was characterized according to the AOAC, an optimization of the spray drying process with a central composite experimental design. The powder's bulk and tapped density, solubility, and anthocyanin content were determined. The variation in zinc and folic acid content over a storage period was measured. The moisture content of the fresh blackberries was 89%. The solubility and anthocyanin content of blackberry powder were 86% and 0.263 mg cyanidin-3-glucose/g, respectively. The optimal spray drying conditions were: 23.6% solid content and an air inlet temperature of 167.92 °C. The bulk density of the powder did not change with storage time ($p > 0.05$); the zinc and folic acid content in blackberry powder was 144 and 90 (µg/100 g), respectively. A blackberry powder fortified with zinc and folic acid was obtained by spray drying, guaranteeing 30% of the daily nutritional requirement for pregnant women and children, in a 50-gram portion of powder.

Keywords Blackberry · Spray drying · Folic acid · Zinc · Pregnant women

Introduction

The Sustainable Development Goals (SDGs) are a group of suggestions and methods designed to eradicate poverty, safeguard the environment, and enhance the well-being and opportunities of individuals worldwide on a global scale. The United Nations member countries adopted 17 Goals in 2015 as part of the 2030 Agenda for Sustainable Development, thus outlining a 15-year timetable to accomplish them. SDG 2 aims to establish a hunger-free world

---

✉ Oscar Vega-Castro
oscar.vega@udea.edu.co

Vargas-Marulanda Diego
diego.vargasm1@udea.edu.co

Castro-Tobón Santiago
santiago.castro4@udea.edu.co

Vallejo-Marulanda Laura
laura.vallejo1@udea.edu.co

Vanegas-Arboleda Valentina
valentina.vanegas@udea.edu.co

Henao-González Daniel
alberto.henao@udea.edu.co

Gómez-Narváez Faver
faver.gomez@udea.edu.co

[1] Grupo Tendencias, Universidad de Antioquia-Campus Carmen de Viboral, Km 6 vía Rionegro- La Ceja, Bloque 3 oficina 109, Antioquia, Colombia

[2] Grupo de Investigación BIOALI, Universidad de Antioquia, Bloque 2 oficina 105. Cl. 67 #53-108, Medellín-Antioquia, Colombia

by 2030, while SDG 3 works to ensure global well-being and health for all individuals. However, despite the existence of policies for the implementation and fulfillment of the SDGs, there remains a deficiency in resources, policies, research, and coverage to ensure their fulfillment by 2030. Indeed currently, 30% of the world's population, approximately 2.44 billion people, still suffers from food insecurity and malnutrition [1], with children and pregnant women the most vulnerable [2]. Approximately 149 million children globally experience nutrition-related problems, resulting in diseases like diabetes and cardiovascular, lung, and kidney ailments, as well as stunted growth and cognitive impairments [3]. Additionally, around 20 million pregnant women worldwide suffer from malnutrition, impacting fetal growth and development and causing complications like anemia, hemorrhage, and hypertension during pregnancy [4]. Both pregnant women and children under five years old commonly experience deficiencies in vital nutrients, such as vitamin A [5], iron [6], zinc [7], and folic acid [8]. On a global scale, almost 17% of the population experiences zinc insufficiency [9], while 32.8% encounter problems associated with insufficient levels of folic acid, iron, and vitamin A [10]. These deficiencies lead to conditions such as anemia, cardiovascular diseases, neurological problems [11], diarrhea, and pneumonia [12].

It is well known that zinc and folic acid play a vital role in the growth and development of children and pregnant women [13]. Inadequate zinc intake during pregnancy can result in hypertensive problems, low birth weight, early birth, and gestational diabetes mellitus [14]. Zinc plays a vital role in cell division, the process of organ differentiation, and the development of fetal organs [15]. Moreover, the intake of zinc in children below the age of 10 has a significant impact on their growth and the development of their immune system [16]. On the other hand, folic acid is essential for the synthesis of nucleic acids, amino acids, and DNA [17]. Folic acid deficiency can cause neural tube defects, anemia, and congenital heart diseases in the fetus [18], as well as the development of preeclampsia [19] and premature births [20].

Given these concepts, it is recommended that both children and pregnant women consume foods rich in folic acid and zinc. Asparagus [21], lettuce [22] and chard [23] are examples of food groups that contain these micronutrients. For instance, spinach, eggs, and legumes are significant sources of zinc [24]. However, many of these foods are challenging to access for vulnerable populations as they require preservation systems like refrigeration [25] or freezing [26]. Additionally, they have a short shelf life, typically lasting 2 to 3 days [27] and come with acquisition costs [28]. A potential solution to these challenges lies in food fortification, which, compared to supplementation, represents a lower cost and broader coverage [28]. Hence, it is imperative to investigate alternative food choices that are readily available, easily consumed, and feasible substitutes for at-risk groups, particularly children and pregnant women. Previous studies have shown that zinc and folic acid have been successfully added to different foods. For example, zinc has been added to Cheddar cheese [29], millet flour [30], kiwi puree and skimmed milk [31], while folic acid has been added to wheat flour [32], cape gooseberries [33], fruit juice powders [34], and different types of drinks [35].

Besides, blackberries have become one of the most desired fruits worldwide due to its nutritional qualities, which include antioxidants, phenolic compounds, tannins, flavonoids, and hypoglycemic activity [36]. In addition, blackberries are rich in vitamin C [37] and minerals such as potassium, calcium, and magnesium [38], and also possess sensory attributes such as sweet and acidic flavors, astringency, and a firm texture [39]. Moreover, under various temperature and moisture conditions, the shelf life of blackberries can range from 1 to 15 days [40]; for example, under normal conditions in a fresh market, they typically have a shelf life of 2 to 3 days [41]. Since blackberries are generally prone to damage due to factors such as inadequate post-harvest handling, high moisture content, and vulnerability to fungal attacks [42], it is important to explore transformation options for prolonging the shelf life of blackberries. Several techniques for preserving and transforming blackberries have been documented, such as cooling [43], freezing [44], drying [45], pasteurization [46], microwave, and ultrasonic treatments [47]. Moreover, blackberries are utilized in the manufacturing of ice creams [48], jams [49], pulps [50], jellies [51], and juices [52].

Despite the importance of the methods mentioned above, a technology that effectively preserves the functional, sensory, and nutritional qualities of foods is spray drying. Spray drying is a technology especially applied to products highly sensitive to heat, this method transforms a liquid or pasty food into a powder by disintegrating the liquid into small, atomized particles with high pressure in contact with contact hot air [53]. This continuous process operation involves several stages, including atomization, mixing of the spray and air, evaporation, and product separation [54, 55]. Among the most important parameters in spray drying are the drying temperature and the carrier agent concentrations. The dryer's inlet temperature is the temperature of the air when it enters the drying chamber of the equipment, which directly affects the heat and mass transfer phenomena in the food droplet. A high inlet temperature (> 120 °C) makes the drying process go faster because more heat is transferred between the droplet and the drying air. This can cause an external layer to form quickly in the droplet, which can result in porous particles or particles with corrugations on their surface. In this way, the inlet temperature mainly affects the shape and size of the particles as well as the final moisture content of the powdered products; a higher inlet temperature leads to lower humidity in the final product [56]. Besides, carrier or drying agents, also called drying adjuncts, encapsulating agents, or wall material, refer to biodegradable substances generally recognized as safe for food products. These agents are used during drying processes to increase yield and lower problems that come with heating food matrices [57].

Furthermore, spray drying is an excellent alternative to other drying methods because it is an easy process to scale up industrially as well as an economical technique that generates high-value products while preserving their quality attributes [58]. Spray drying has been used to produce powders from different fruits, including Passion Fruit [59], Noni [60], Jamun [61], Cagaita [62], Gac [63], and Guava [64].

Studies on the use of spray drying technology on blackberries have been undertaken by [65–69]. These studies [66, 69] have successfully produced powders with moisture content below 6%, rendering them highly stable [65]. It has also been found that, although the spray drying temperature affects the anthocyanin content of the blackberry powder due to the sensitivity of the pigment to temperature, the use of maltodextrin decreases the hygroscopicity and moisture content of the blackberry powders obtained [66]. On the other hand, researchers have studied the effect of using mannitol as a thermoprotective agent for anthocyanins and polyphenols in the spray drying of blackberries; they found that without mannitol, the content of anthocyanins and polyphenols decreased by 30 and 24%, respectively. With the use of mannitol, the losses of anthocyanins and polyphenols were 13 and 6%, respectively. The above demonstrates the importance of using wall or thermoprotective materials to conserve bioactive compounds of interest [68]. Additionally, it has been reported that the drying process of blackberries can involve the use of carrier agents such as Arabic Gum, mannitol [68], and maltodextrins [65, 69]. Carrier agent is one of the most important factors in spray drying of sugar-rich materials, such as fruit and vegetable juices, because its use reduces the stickiness and hygroscopicity of powdered products, generating higher yield percentages [58]. For instance, a higher maltodextrin content decreases the moisture content of the products obtained [70]. Both mannitol and maltodextrin act as thermos protectors for bioactive substances present in blackberries, such as polyphenols [68]. Finally, the use of pigments such as flavonoids and cinnamic acids is recommended to improve the shelf stability of anthocyanins present in blackberries [69].

Besides, spray drying is also an appropriate method for encapsulating bioactive compounds, vitamins, and colorants, among other substances. In this regard, encapsulation of vitamins such as B12 and C [71], anthocyanins and phenolic compounds [72], antioxidants [73], and carotenoids [74] has been documented. Regarding blackberries, studies have produced powders enriched with iron [75], fiber [76], and β-Cyclodextrin [77]. However, the currently available research does not demonstrate the addition of both folic acid and zinc into spray-dried blackberries powders.

Hence, the main goal of this research was to develop a blackberry powder fortified with zinc and folic acid. To achieve this, a proximal analysis of the blackberry was initially carried out, and subsequently, the spray drying process was optimized through the response surface methodology. After that, some of the blackberry powder's physical, bioactive, and proximal properties were found. Over the next 45 days, the zinc, folic acid, and antioxidant content were also measured. This study contributes to the accomplishment of the WHO's and SDGs 2, 3, and 9.

Materials and methods

Reagents and Materials

The blackberries were purchased at Plaza Minorista, a farmers' market in the city of Medellin, Colombia, selecting fruits at maturity stages 4–6 according to NTC 4106 and NTC 410 standards. The blackberries were harvested on Mr. Javier Rios's farm in the village of Pantanillo, located in the Santa Elena district of Medellin. For disinfection, a solution of Citrosan (Diken, Mexico) and water was used, with a ratio of 2.5 mL Citrosan/L water, in which the berries were immersed for 5 min [78].

The procedure to determine of antioxidants involved the use of DPPH (Merck Millopore, USA) and methanol (J.T. Baker, USA). For anthocyanins, KCl (Carlo Erba, Italy) at pH 1.0 and sodium acetate (PanReac AppliChem, Germany) at pH 4.5 were used. Acetone (PanReac AppliChem, Germany), Folin-Ciocalteu reagent (Merck KGaA, Germany), Na_2CO_3 (EMSURE, Germany), and gallic acid (Merck KGaA, Germany) were used to measure the amount of polyphenols. To make the blackberry dispersion, 99.5% pure Smart Chemical brand folic acid batch 201,905,018 and Quiminaturales brand zinc citrate batch MC 21,112,019 were used. Additionally, Tween 60 surfactant from Bell Chem Internacional S.A. batch 161029J3152 and maltodextrin (DE: 18–20) from LLC Interstarch Ukraine batch 61 were used.

Blackberry Proximal Analysis

The blackberry was characterized through the determination of moisture, ash, fat, total nitrogen, and total protein content (using the coefficient 6.25) [79]. Additionally, soluble, insoluble, and total fiber were determined [79]. According to Vega-Castro et al. [80], Eq. 1 served as the basis for calculating the total carbohydrate content (%CH).

$$\%CH = 100\% - \sum (\%Moisture + \%Ashe + \%Fat + \%Protein) \tag{1}$$

The soluble solids (°Brix) were measured using a digital refractometer from Bellingham + Stanley [79]. Finally, the water activity (aw) was determined using an Aqualab-Pre analyzer (Lab-Ferrer, Spain), following the methodology provided by Pui et al. [81].

Preparation of the Dispersion

Once the blackberries were disinfected as described by Betoret et al. [78], they were processed in a pulper with a standard No. 16 sieve with an opening of 1180 microns (Estructuras y Montajes, Colombia). The dispersion formulations were prepared based on 300 g of blackberry pulp with 7.6 °Brix as a reference, which was mixed with 5% of Tween 60, and different concentrations of maltodextrin (Table 1); maltodextrin was chosen because it provides better encapsulation and protection of bioactive compounds such as polyphenols and antioxidants than other carrier agents [58]. Then, quantities between 34 and 46 mg of zinc citrate and 1.2–1.6 mL of 0.2 mg/ml of folic acid solution were added. Finally, all components were homogenized at 14,000 rpm in 2 cycles of 3 min using an Ultra-Turrax® MDT-G25 (Kinematica, Switzerland) and then refrigerated at 4 ± 0.5 °C [71, 82, 83].

The analytical balance (Radwag, Poland) was used to weigh all components of the dispersion, with a precision of 0.1 mg. The zinc and folate levels were determined based on a serving size of 50 g of powder product and using a 30% allocation of the daily value, as stipulated in Resolution 810 of 2021 by the Ministry of Health and Social Protection of Colombia.

Table 1 Experimental conditions were applied to study the temperature and solid content concentration using an MSR-DCC 2^2 with 4 axial and 3 central points

Treatment	Temperature drying (°C)	Solid Content (%MD)*
1	180.00	25.00
2	182.07	30.00
3	170.00	25.00
4	175.00	30.00
5	180.00	35.00
6	167.92	30.00
7	175.00	37.07
8	170.00	35.00
9	175.00	30.00
10	175.00	30.00
11	175.00	22.92

*Maltodextrin content in the dispersion (%w/w)

Spray Drying

For the spray drying process, the methodology, briefly modified, was based on Leyva-Porras et al. [84]and Gong et al. [85]. Samples were prepared with maltodextrin concentrations ranging from 22.93 to 37.07%. A TP-S15 spray dryer (Xi'an Toption Instrument Co., China) was used for drying, with air inlet temperatures ranging from 168 to 182 °C and outlet air temperatures ranging from 82 to 98 °C. The pump power was set at 6%, equivalent to a flow rate of 1.26 ml/min of the blackberry dispersion. Additionally, the air power operated at 100%, corresponding to an air flow rate of 5.5 m3/min. At the end of the process, the samples were placed in separate containers and kept in darkness [66]. The decision to use maltodextrin concentration and drying temperature parameters for this investigation was determined based on the results of previous research. For instance, maltodextrin at levels of about 23–40% helps to keep polyphenols, antioxidants, and anthocyanins safe, as well as giving spherical particles a smooth surface that makes them less likely to stick together in the end product [86]. Furthermore, temperatures in the range of 170–185 °C favor technological properties, such as humidity, water activity, density, and flow properties, as well as the conservation of polyphenols and antioxidants [86].

Powder recovery was determined according to the method indicated by Muzaffar and Kumar [87] by calculating the percentage ratio between the total mass of the recovered product after the drying process and the total solids content in the feed material.

Determination of Antioxidants and Total Polyphenols

The antioxidant and total polyphenol content of the blackberry powders were determined using the methodologies described as follows.

Preparation of Extract

Preparing an extract using the Contreras-Calderón [88] methodology was necessary to determine the antioxidant and polyphenol content. For this purpose, 0.5 g of the sample (pulp or dried material) was weighed and mixed with 4 ml of methanol and water in a 50/50 ratio. The mixture was vortexed (BenchMixerTM, USA) for one minute and subsequently subjected to ultrasound treatment (Elmasonic EASY, Germany) for 15 min at a frequency of 50/60 Hz. Then, the mixture was centrifuged at 6000 rpm for 15 min using a centrifuge (BOECO C-28 A, Germany). The supernatant was then transferred to a 25-mL flask previously prepared with filter paper. This process was repeated three times with the methanol/water solution. Once the process was completed, the same ultrasound and centrifugation procedure was carried out with an acetone/water solution in a 70/30 ratio. After completing the procedure with the acetone/water solution, the volumetric flask was filled with distilled water. The samples were then stored in refrigerators and protected from light.

Total Polyphenols

The Folin-Ciocalteu assay was used to measure the total amount of polyphenols, using a method adapted from Osorio-Arias et al. [89] and the one described by Contreras-Calderón [88]. Here, 20 µL of the extract was diluted in 1600 µL of distilled water and mixed with Folin-Ciocalteu reagent (100 µL) and 300 µL of sodium carbonate solution (20% w/v). After 60 min in the dark, the absorbance was measured at 725 nm using a Varian Cary 50 UV-Vis spectrophotometer. Different gallic acid solutions (concentrations ranging from 0 to 1000 ppm) were used to create the calibration curve. The results were expressed in milligrams of gallic acid equivalents per gram of solids (mg of GAEs/g). Measurements were performed in triplicate.

Antioxidants

For the determination of antioxidants, the FRAP and ABTS methods were employed, as described by Brand-Williams et al. [90]. A standard curve was constructed using a 10 ml volumetric flask filled with 5 ml of methanol and 5 ml of water for both methods, where 0.01 g of Trolox reagent was weighed. For the FRAP method, 30 µL of standard solution or sample extract was mixed with 90 µL of distilled water and 900 µL of FRAP reagent. The samples were then incubated for 30 min and measured in the spectrophotometer at a wavelength of 595 nm, using acetate buffer as the blank. Trolox solutions (concentrations ranging from 0 to 500 ppm) were used for the calibration curve. Measurements were performed in triplicate. For the ABTS method, 100 µL of the standard solution or sample extract was mixed with 1000 µL of the ABTS + solution. The samples were then incubated for 30 min and measured in the spectrophotometer at a wavelength of 730 nm, using ethanol as the blank. Trolox solutions (concentrations ranging from 0 to 500 ppm) were used for the calibration curve. Measurements were performed in triplicate.

Determination of Anthocyanins

For the determination of anthocyanins, the methodology of AOAC 2005 [79] was followed. This method is based on spectrophotometry and the color change of the anthocyanin pigment at different pH levels. Initially, dilutions of potassium chloride at pH 1.0 and sodium acetate at pH 4.5 were prepared in 50-ml volumetric flasks. The blackberry extract previously prepared was brought to a ratio of 1:4 (1 part sample and 4 parts buffer). The two obtained solutions were used and allowed to rest for 20–50 min. Subsequently, measurements for each solution were taken using a Varian Cary 50 UV-Vis spectrophotometer at an absorbance of 520 nm and 700 nm. The samples were then read against a blank of distilled water with a 1 cm cell path length. For the calculation of anthocyanins, cyanidin-3-glucoside equivalence was obtained by following Eqs. 2 and 3:

$$A = (A_{520} - A_{700})_{pH1.0} - (A_{530} - A_{700})_{pH4.5} \tag{2}$$

$$CAT = \left(\frac{mg\ cyanidin - 3 - glucoside}{g}\right) = \frac{A * MW * DF * 1000 * EV}{\varepsilon * 1 * SW} \tag{3}$$

Where: *CAT*: Anthocyanin pigment content (mg/g): *A*: Change in absorbance obtained in the spectrophotometer, *MW*: Molecular weight for cyanidin-3-glucoside 449.2 g/mol. *DF*: Dilution factor. EV: Extract volume ε: Molar extinction coefficient for cyanidin-3-glucoside (26900 L/mol.cm). SW: Sample weight.

Folic Acid Determination

The methods described by Lopera and Gallardo [91] and Khan et al. [92] were used to determine the amount of folic acid in the blackberry powder. Liquid-liquid extraction and quantification were performed by liquid chromatography coupled with mass spectrometry (LC-MS/MS). For the folic acid measurement, 0.2 mL of a 50% citric acid solution was added to adjust the pH to 4.3, followed by the addition of 70 µL of dextrozyme GA enzyme at 60 °C in a water bath for 10 min. Then, 5 mL of citrate-phosphate buffer solution at pH 7.5, adjusted with 10% NaOH, was added to each sample. The mixture was shaken for 5 min in an ultrasonic bath, and a 2 mL aliquot was taken, filtered, and analyzed by HPLC. For the HPLC analysis, a Perkin Elmer HPLC with a 200 EP series diode array UV detector and a SORBAX SB-C18 LC column (150 × 3 mm x 3.5 µm) was used. The equipment conditions as follows: a temperature and wavelength of 30 °C and 254 nm, respectively. The mobile phase consisted of 0.017 M potassium dihydrogen phosphate, a

0.22% tetrabutylammonium hydroxide modifier, and methanol in a ratio of 66:34.

Zinc Determination

The analysis of zinc in the blackberry powder was carried out according to the technique suggested by Cherfi et al. [93], using an atomic absorption spectrometer Unicam model Solar-929 (Cambridge, UK). The measurements were conducted using an air-acetylene flame, with a bandwidth of 0.5 nm, a lamp current of 10 mA, an air flow rate of 6 L/min, and an acetylene flow rate of 2.5 L/min. The wavelength used for measuring zinc was 217 nm.

Color Measurement

For the color measurement of both fresh blackberries and blackberry powder, the CIELAB methodology was used, with slight modifications based on Cuesta-Riaño [94] and adapted for smartphone use according to the study made by Sáez-Hernández [95]. The L*a*b parameters were determined using the “Colorimeter App”; the distance between the phone and the samples was approximately 10 cm. Measurements were taken from an iPhone XR with a 12 MP camera. The obtained values were initially expressed in terms of RGB but were later converted using the “Colorlab” app to express them in terms of the Lab color space, also referred to as CIELAB.

Solubility Measurement

The solubility of blackberry powder was measured using the approach described by Santhalakshmy et al. [61]. One gram of the sample was mixed with 100 ml of distilled water using a vortex (BenchMixer™, USA) for 5 min. The solution was then centrifuged (BOECO C-28 A, Germany) at 3000 rpm for 5 min and allowed to rest for a minimum of 30 min. The supernatant was transferred to pre-weighed petri dishes and dried in an oven at 105 °C for 5 h. Solubility was calculated based on the weight difference (%), according to Eq. 4:

$$\%Solubility = \frac{Wi - Wg}{Wf - Wg} \times 100 \tag{4}$$

Where: W_i is the initial weight of the powder, W_f is the final weight of the powder, and W_g is the weight of the petri dishes.

Moisture Content and Water Activity (aw)

To determine the moisture content of the blackberry powder, the method outlined by Melo-Guerrero et al. [96] was employed, using a thermobalance MA 210.X2 (Radwag, Poland), at a temperature of 70 °C, and weight stabilization at 120 s with a 1 mg difference. Then, 3 g of blackberry powder was placed in the pre-weighed tray, and analyzed until a constant weight was achieved. Water activity (aw) was measured following the methodology given by Pui et al. [81] and using an Aqualab-Pre analyzer (Lab-Ferrer, Spain).

Bulk Density and Tapped Density

For bulk density determination, a volume between 6 and 8 ml of the blackberry powder was poured into a 10-mL graduated test tube, and then the powder mass was measured. For taped density, the test tube was dropped 50 times from a height of 10 cm, and the new volume of the compacted powder was registered. The densities were calculated using Eq. 5a and 5b, following the methodology proposed by Tonon et al. [97].

$$\rho_b = \frac{w_p}{V_1} \tag{5a}$$

$$\rho_t = \frac{w_p}{V_2} \tag{5b}$$

Where: ρ_b: bulk density (g/cm^3), w_p: powder weight (g), V_1: initial powder volume (cm^3), ρ_t: tapped density (g/cm^3), and V_2: compacted powder volume (cm^3).

Experimental Design

To find the best spray drying conditions for the bioactive, functional, and technological properties of blackberry powder, a response surface methodology (RSM) was implemented, involving with 11 experiments that used a rotatable central composite design (CCD) 2^2 with 4 axial points and 3 central points. The independent variables were maltodextrin concentration (25–35%) and air inlet temperature (170–180 °C). The dependent variables were moisture, water activity (aw), color, antioxidant capacity, polyphenol content, and anthocyanin content (see Table 1).

The response variables were determined using RSM, and the experimental values were fitted to the following second-order equation, as shown in Eq. 6.

$$Y = b_0 + \sum {}_{i=1}^{2} b_i x_i + \sum {}_{i=1}^{2} b_{ii} X_i^2 + \sum {}_{i<j=1}^{2} b_{ij} X_i X_j \tag{6}$$

Table 2 Summary of the proximate analysis of fresh blackberries, harvested in Santa Elena, Medellin, Colombia

Analysis	Value	Units
Moisture	84.39 ± 7.310	g/100 g
Ash	0.42 ± 0.040	g/100 g
Fat	< 0.33	g/100 g
Protein	1.28 ± 0.113	g/100 g
Carbohydrates	13.91	g/100 g
Calories	28.48	Kcal/100 g
Crude fiber	2.58 ± 0.485	g/100 g
Soluble dietary fiber	1.33 ± 0.403	g/100 g
Insoluble dietary fiber	6.74 ± 0.739	g/100 g
Total dietary fiber	8.07	g/100 g
Antioxidant Content (FRAP)	16.26 ± 0.79	µmolTrolox/g

Where: Y is the response variable, b_0 is a constant, b_i are coefficients of the model linked to a linear effect, b_{ii} are coefficients related to the quadratic effect, b_{ij} are constants for the interaction effect, and X_i and X_j are the variables.

Finally, to optimize the response variables, a multiple response methodology was carried out through the desirability function. The aim is to convert each response y_i into a desirability function d_i, which can range from 0 to 1. In general, the value of d_i is 1 when the response variable y_i achieves the optimization goal. However, if the value of the response variable y_i is not in the acceptability region, $d_i = 0$. According to Saavedra et al. [98], each response should be standardized in the desired function di, represented as $d_i = h_i(y_i)$, following Eq. 7.

$$D = (d_1 d_{2\ldots} .d_m)^{1/m} \tag{7}$$

With the optimized drying conditions, additional drying was performed in triplicate. Time-dependent data were analyzed using a randomized experimental design, with time as the independent variable having four levels (day 0, day 15, day 30, day 45). The dependent variables included moisture, bulk density, solubility, folic acid content, and antioxidant content (ABTS). The data were analyzed using a 95% ANOVA and a 95% LSD-Fisher multiple range analysis.

Results and Discussion

Proximate Analysis of Blackberries

The results of the proximate analysis of fresh blackberries are shown in Table 2. Overall, the values for moisture (84.39%) and ash (0.42%) are like those found by Hassimotto et al. [99], who evaluated these parameters for blackberries grown in Brazil. However, as shown in Table 2, the carbohydrate content (13.91%) was higher than the one reported by Hassimotto et al. [99]. Likewise, Monroy et al. [100] reported values for ash, protein, fat, and fiber that match those in Table 2. Although the values presented in Table 2 may vary from those found by other authors due to environmental conditions, cultivation practices, and fruit variety, they contribute to the characterization of fresh blackberries, considering the scarcity of reports on this matter.

Spray Drying

The experimental design in Table 3 displays the results for different response variables of the blackberry powder, including moisture, water activity (aw), antioxidants, polyphenols, solubility, and color.

The results in Table 3 show that the moisture content obtained for blackberry powder ranged from 0.95 to 3.19%, corresponding to experimental conditions 6 and 1, respectively. These moisture values for blackberry powder are comparable to those reported by Ferrari et al. (2012a) [66], who obtained moisture values for blackberry powder between 0.47 and 2.44% by spray drying. Furthermore, the moisture content of blackberry powder is comparable to that of other fruit powders, such as cupuassu powder [101], jackfruit powder [81], and Chinese plum powder [102], where

Table 3 Blackberry powder properties measured for each run at the end of spray drying process

Treatment	Moisture (%)	Aw	FRAP (µmol Trolox/g)	ABTS (µmol Trolox/g)	Polyphenols (mg Gallic Acid equi/g)	Anthocyanin (mgcyanidin-3-glucoside/g)	L	a*	Solubility (%)
1	3.19	0.35	13.284	7.553	10.662	0.221	52.83	53.67	86.31
2	2.82	0.34	13.94	7.488	9.319	0.292	48.3	52.6	89.29
3	2.26	0.26	14.836	7.635	10.712	0.052	44.03	50.37	86.56
4	2.12	0.35	12.713	6.282	8.044	0.819	40.23	49.87	87.95
5	1.6	0.28	12.729	5.85	7.908	0.113	41.03	52	87.96
6	0.95	0.29	12.375	6.365	8.334	0.091	39.3	48.77	81.54
7	1.25	0.26	11.446	5.677	6.372	0.525	36.9	50.43	87.71
8	1.31	0.25	10.766	5.462	7.348	0.445	32.47	49.13	87.91
9	1.2	0.26	13.946	6.289	7.334	0.145	40.83	50.53	87.81
10	1.17	0.3	12.896	7.053	9.532	0.128	44.23	49.83	87.78
11	2.21	0.42	16.075	7.209	9.855	0.068	55.63	49.03	84.64

the powder moisture ranged between 1.59 and 6.03%. Regarding the aw of blackberry powder, the values obtained ranged from 0.25 to 0.35. Similar aw values in blackberry powders were found by Farias-Cervantes et al. [103], who obtained values of 0.19–0.45 for spray-dried blackberry powder, other comparable values for tangerine powders were obtained [104]. Based on the values of aw and moisture obtained for the blackberry powder in Table 3, it can be concluded that this product is suitable for marketing since fruit powders with low moisture content have good stability and a longer shelf life [105]. Additionally, the moisture content of this powder falls within the acceptable range for industrial production of spray-dried fruit [106]. Finally, it can also be considered a stable product since foods with aw < 0.6 are generally regarded as microbiologically stable [107].

As shown in Table 3, the antioxidant content determined using the FRAP methodology ranged from 107.661 to 160.754 mol Trolox/g. The drying conditions with the highest antioxidant content were at 175 °C with 22.928% maltodextrin. The FRAP values for blackberry powder shown in Table 3 are lower than those reported by Da Fonseca et al. [108], who obtained values of 183.12 µmol Trolox/g for blackberry powders dried at 105 °C. However, they are higher than the values reported by Thaipong et al. [109] for various guava powders, ranging from 15.5 to 33.3 mol Trolox/g.

The antioxidant content of blackberry powder is shown in Table 3, with values ranging from 54.622 to 76.351 µmol Trolox/g using the ABTS method. The highest antioxidant content was obtained with drying conditions at 170 °C and a maltodextrin content of 25%. This range of antioxidant values is similar to findings by Rigon and Zapata [72] and Hassimotto et al. [99], who obtained ABTS antioxidant contents of 67 µmol Trolox/g for blackberries processed by spray drying at 140 °C and 76 µmol Trolox/g for fresh blackberries, respectively.

The total polyphenol content varied between 6.372 and 10.712 mg gallic acid/g (Table 3). The drying conditions at 170 °C and a 25% maltodextrin content resulted in the highest total polyphenol concentration in blackberry powder. Rigon & Zapata (2016) [72] obtained comparable data, reporting a polyphenol concentration of 10.039 mg gallic acid/g for spray-dried blackberries. Antioxidants, including polyphenols, are sensitive to high temperatures [110]; usually, the higher the temperature, the faster the antioxidant degradation. That is why the samples dried at 170 °C exhibited the highest antioxidant and polyphenol content, as it was one of the lowest temperatures in the experimental design. Likewise, an increase in maltodextrin content reduces the antioxidant and polyphenol content, as maltodextrin itself has no antioxidant capacity or polyphenols. A maltodextrin addition results in a dilution of the antioxidant compounds. Mishra et al. [111]and Oberoi and Sogi [112] found similar results in the spray drying of amla juice and watermelon juice.

Table 3 also shows the anthocyanin content of blackberry powder. The values range from 0.052 mg cyanidin-3-glucoside per gram of sample to 0.818 mg cyanidin-3-glucoside per gram of sample, which is equal to 0.51–8.40 mg cyanidin-3-glucoside per liter of extract. The highest anthocyanin content was achieved under drying conditions at 175 °C with a 30% maltodextrin content. These values are similar to those reported by Da Fonseca et al. [108], who found an anthocyanin content of 0.79 mg cyanidin-3-glucoside/g in blackberry powders obtained by spry drying. Anthocyanin values for other powder fruits obtained by spry-drying, such as pomegranates, vary between 5.980 and 8.015 mg cyanidin-3-glucoside/L [113], which are like those reported in this study. The amounts are also about the same or less than what was found in studies that dried blueberries (2.10 to 17.41 mg cyanidin-3-glucoside/g) [114], black rosehips (0.91–2.47 mg cyanidin-3-glucoside/g) [115], and maoberries (0.41–0.94 mg cyanidin-3-glucoside/g) using freeze-drying, convective drying, and microwave drying [116]

With the values of antioxidants, polyphenols, and anthocyanins reported in Table 3, it can be concluded that the blackberry powder obtained in this research agrees with results found by different authors for this fruit and drying method, maintaining significant levels of these characteristic components of blackberries. Therefore, this drying method allows for the preservation of these components in blackberries while enabling fortification.

Solubility percentages for blackberry powder varied between 84.642 and 89.289%, with the highest solubility achieved under experimental condition 2, as shown in Table 3. Rigon and Zapata (2016) [72] reported solubility values for blackberry powders that ranged between 88.2% and 97.4%. Similar solubility values for powders from various fruits have been determined by previous studies, some of which are comparable to those shown in Table 3. The solubility of guava powder was 83.42% [109], *Eugenia dysenterica* was 94.4–97.8% [62], Morus was 87% [117], and *Haematocarpus validus* was 96.62% [118]. In terms of the relationship between solubility values and consumer perception, it is important to clarify that solubility is an important property of spray-dried food products that can directly influence quality and consumer acceptance [119]. High solubility is an essential aspect to achieve excellent product quality and excellent reconstitution behavior [111], as well as to promote the dissolution of organic and inorganic substances such as sugars and salts [120] that directly affect consumer perception. The solubility values found in this work are mostly above 85%, which means that the blackberry powders obtained have high solubility and consequently good consumer acceptance [121]. It can be stated that the solubility values in Table 3 agree with those obtained by various authors, suggesting that blackberry powder can easily dissolve in water, facilitating its application at the household or industrial level.

Experimental Design Analysis

Table 4 presents the p-values for each of the studied response variables, based on the experimental design depicted in Table 1. Equations 8, 9, 10 and 11 show the relationships between independent factors and dependent variables for moisture, polyphenol content, ABTS antioxidant content, and the L color parameter, respectively. Figure 1A, B, C, D and E show the effect of drying air inlet temperature and solid content on the content of antioxidants (ABTS) and antioxidants (FRAP), as well as the solubility and color parameters L and a*, respectively.

$$Moisture : 285.032 - 3.418T + 0.573CS + 0.010T^2 - 0.0064T \times CS + 0.007CS^2 \tag{8}$$

$$Polyphenoles : 574.055 - 6.203T - 1.528CS + 0.017T^2 - 0.0061T \times CS + 0.0030CS^2 \tag{9}$$

$$ABTS : 242.772 - 2.580T - 0.819CS + 0.007T^2 + 0.0047T \times CS - 0.0025CS^2 \tag{10}$$

$$L* : 493.398 - 4.883T - 4.762CS + 0.016T^2 - 0.0024T \times CS + 0.065CS^2 \tag{11}$$

Where: Drying air inlet temperature (T), Solid content (CS), Drying air inlet temperature squared (T^2), and Solid content squared (CS^2).

From Table 4, it can be observed that the moisture content, water activity (aw), and polyphenol content of blackberry powder were not significantly affected by the independent variables or their interactions ($p > 0.05$). The values in Table 4 are consistent with the mathematical model presented in Eq. 6, because the lack-of-fit test for moisture, aw, and polyphenol content produced a p-value greater than 0.05. Additionally, the coefficient of determination (R^2) for these variables explains the behavior of the responses by more than 70%, indicating that the data was well-collected, explains the responses and fits the design model [122]. In general, the polyphenol and anthocyanin content of blackberry powder did not change significantly; instead, they remained constant, a behavior attributed to the quick drying time, consistent with [123].

Regarding the antioxidant content evaluated by the ABTS and FRAP methods, they were significantly affected ($p < 0.05$) by the solids content. As shown in Fig. 1a and b, higher solid content led to lower antioxidant content; however, maltodextrin was able to preserve 78% and 83% of the antioxidant content by ABTS and FRAP, respectively, in accordance with Santiago-Adame et al. [124]. This preservation effect of maltodextrin on antioxidants is attributed to the amorphous structure of maltodextrin, which maintains an amorphous state during the spray drying process. This state favors air expansion within the formed particles, increasing volume to preserve antioxidants [110].

Besides, considering these results, it can be said that sugar-rich materials, such as fruit juices, are difficult to directly spray dry without a carrier agent due to their stickiness behavior and low glass transition temperature, which leads to wall deposition problems and drying difficulties [58]. Alternatively, carrier agents can be employed as an aid in the spray drying process, where the main function is to increase the Tg of the system since these agents are characterized by a high molecular weight, low viscosity, and Tg in a range of 100–188 °C [110]. Shishir and Chen [58] conducted an extensive review of trends in the spray drying of fruits and vegetables, in which they summarized several studies that employed various carrier agents, concluding that, in most of them, maltodextrins were the most efficient carriers to preserve heat-sensitive compounds during the spray drying process. The higher conservation capacity of maltodextrin is due to its physicochemical properties, which

Table 4 Analysis of variance (ANOVA) of the DCC 2^2 with 4 axial points and 3 central point design

Source	*p* value								
	Moisture	Aw	FRAP	ABTS	Polyphenols	Anthocyanins	L	a*	Solubility
A	0.1271	0.2735	0.2979	0.2698	0.6095	0.923	0.0387*	0.0091*	0.0092*
B	0.1253	0.1383	0.0272*	0.0404*	0.0735	0.493	0.0147*	0.4909	0.0013*
A^2	0.3641	0.8242	0.6405	0.4413	0.4554	0.62	0.6973	0.0736	0.0398*
AB	0.6135	0.5743	0.1184	0.6489	0.812	0.592	0.9607	0.6393	0.2561
B^2	0.4965	0.7239	0.6479	0.7638	0.8855	0.823	0.2125	0.6139	0.0022*
Lack of fit test	0.6443	0.5137	0.5043	0.5406	0.8134	0.956	0.5001	0.0799	0.0178*
R^2	78.740	62.570	89.366	89.366	81.864	38.86	94.538	76.699	89.679

A: Temperature; B: Solid Content

*Values $P < 0.05$ indicate that there is a significant impact. The p-value > 0.05 of the lack-of-fit tests indicates that the values of the response variables fit a second-order model

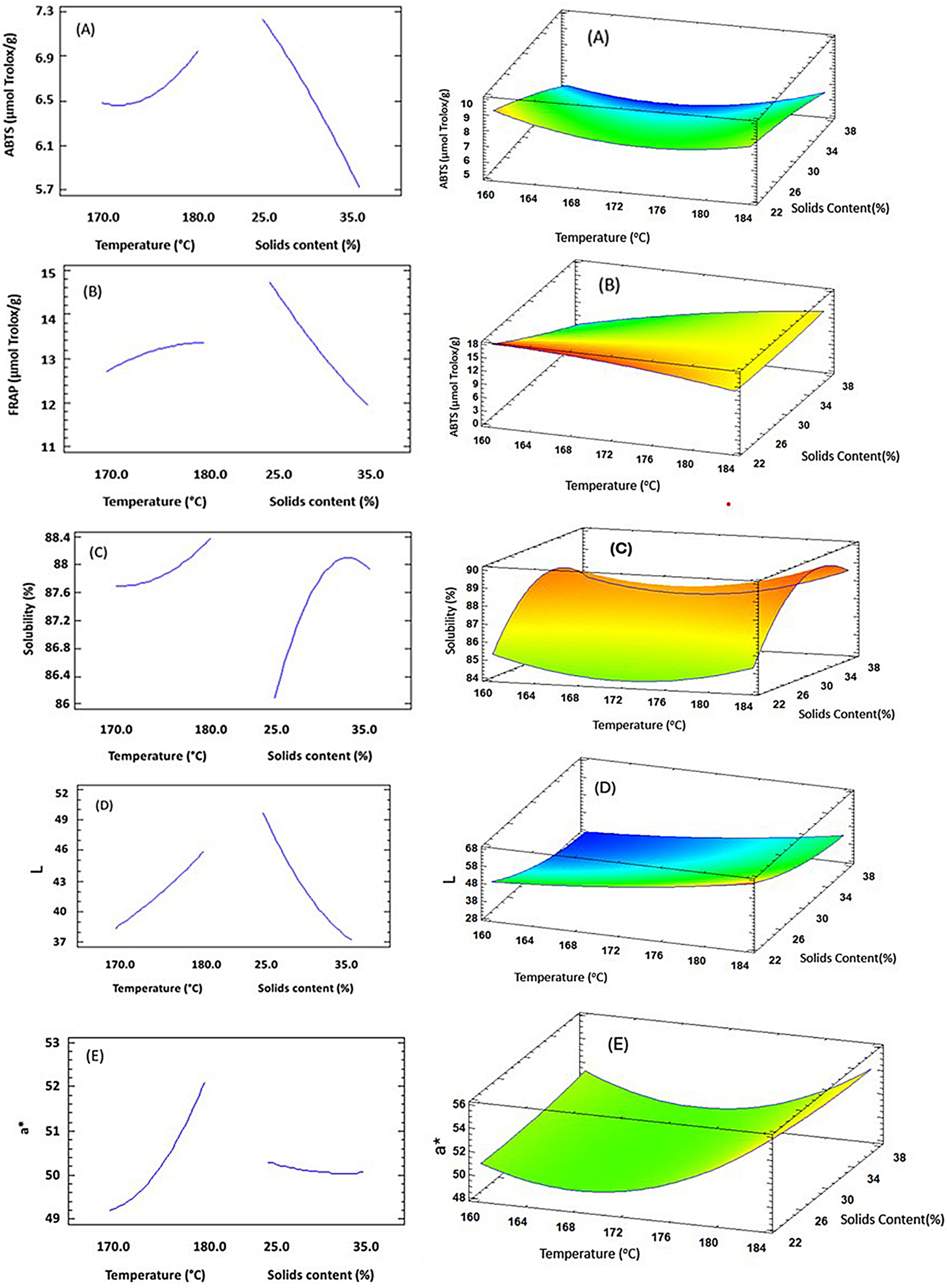

Fig. 1 Effects and surface response graphics of drying temperature and solids content on **(A)** Antioxidants (ABTS), **(B)** Antioxidants (FRAP), **(C)** Solubility, **(D)** L parameter and **(E)** a* parameter

Table 5 Optimization criteria for response variables in the blackberry powder spray drying process

Response Variable	Optimization criteria
Moisture content	Minimized
aw	Minimized
Antioxidants - FRAP	Maximized
Antioxidants - ABTS	Maximized
Polyphenols	Maximized
Anthocyanins	Maximized
Solubility	Maximized
Zinc Content	Maximized
Folic Acid Content	Maximized

keep the amorphous microstructure in all water activities [110], thus avoiding the rubbery state, where most degradation reactions speed up because of its high molecular mobility. Finally, the lack-of-fit test for all variable response was higher than $p > 0.05$, which means that these variables fit the model of Eq. 6. Indeed, in Table 4, the R^2 for ABTS and FRAP was 89% and 84%, respectively, which indicates that the data shown in Table 3 correctly explains the variation of these parameters.

Table 4 shows that both linear and quadratic effects had significant effects on the solubility of blackberry powder ($p < 0.05$). For instance, Fig. 1c indicates that the solubility of blackberry powder rises when the solid concentration of the dispersion increases and as the drying air inlet temperature is increased. An increase in the air inlet temperature during the drying process leads to a higher solubility of powder since the heating of starch structures contained in maltodextrin prevents the organization of starch granules, facilitating water migration to the starch-like structure of maltodextrin [125]. Furthermore, lower powder moisture is associated with higher solubility [118]. The increase in powder solubility with higher solid content is attributed to the addition of maltodextrin to obtain more solids, improving the solubility properties of powders, as observed in sweet potato powders [126] and mango powders [127].

As for the color parameters, the analysis of variance shown in Table 4 indicates that both drying air inlet temperature and solid content significantly affected the color parameter L of the blackberry powder ($p < 0.05$). Figure 1d shows that while a higher drying air inlet temperature increased the L parameter, consistent with the results of Sarabandi et al. [128], a higher solids content decreased it [61]. Only the drying air inlet temperature ($p < 0.05$) had an impact on the color parameter a*, increasing it, as shown in Fig. 1e. In general, the color parameters of powders change depending on the drying parameters and the type of encapsulating agent [128]. This behavior is due to the fact that, according to Santhalakshmy et al. [61], most encapsulating agents are white (such as Maltodextrin powder) [61]. The whiteness of maltodextrin has an impact on the color properties of blackberry powders, leading to increased brightness and decreased redness, according to findings by Wei and Sulaiman (2022) [129].

Optimization and Time Analysis

Table 5 shows the optimization criteria for the response variables in the spray drying process of the blackberry powder. Equation 7 was applied to optimize the drying process and enhance the properties of the blackberry powder, minimizing the moisture content and maximizing the antioxidant content (by the FRAP and ABTS + methods), as well as the content of total polyphenols. In that sense, the optimal conditions of the process were a drying air inlet temperature of 167.92 °C and a solids content of 23.608% with a desirability of 85.5%, as seen in Fig. 2. The optimal drying conditions were done in triplicate. The established drying conditions yielded a powder recovery of 63.9%, in line with the findings of Muzaffar and Kumar [87] and Henao-González et al. [86], who reported powder recovery percentages of 68.4% for tamarind pulp and 71.4% for strawberry pulp, respectively. Differences in recovery percentages may

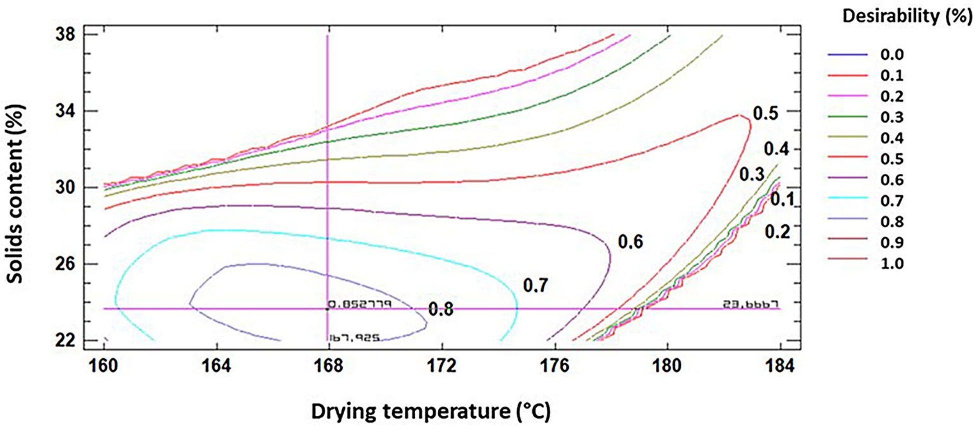

Fig. 2 Contour plot for the desirability function for the optimization of multiple responses of the spray drying process

be due to factors such as inlet air humidity, carrier agent concentration, and feed flow rate [58].

Table 6 displays the changes in antioxidants (FRAP), total polyphenol content, anthocyanins, moisture, water activity, bulk and tapped density, folic acid, and zinc levels over time (0, 15, 30, and 45 days) for blackberry powder under the optimal conditions of the spray drying process. Figure 3A, B, C, D, E and F y 3 H show the mean graphs with a significance of 95% for moisture, bulk density, solubility, folic acid, zinc, antioxidant-FRAP, antioxidant-ABTS, anthocyanin of the blackberry powder over time.

The moisture content of the blackberry powder was significantly affected by the storage time ($p < 0.05$), as shown in Fig. 3a, where a longer storage time resulted in a higher moisture content of the product. This increase could be attributed to the sugar content of blackberries and the presence of maltodextrin in the formulation, which can enhance water adsorption by the powder [130]. Similar increases in moisture content have been observed for fruit powders such as tamarind powder [131] and black mulberry powder [117].

Table 6 shows that, throughout the 45-day storage of blackberry powder, the average preservation percentages for the antioxidants FRAP, ABTS, and anthocyanins were 41%, 32%, and 22%, respectively. The content of the antioxidants FRAP, ABTS, and anthocyanins was significantly impacted by the storage time, as illustrated by Fig. 3F and G, and 3H ($p < 0.05$). Based on previous results for black carrot (*Daucus carota L.*) [132] and bayberry (*Myrica gale*) [133], which have indicated similar degradation in and over time, the observed phenomenon is likely caused by both kinetic degradation and light exposure. Several factors that could cause the anthocyanin content in the blackberry powder to drop over time, including light, temperature, oxygen, or enzyme action [134]. However, since the blackberry powder was stored in a package whose atmosphere was mostly oxygen, it is likely that oxygen was the cause of the loss of anthocyanins. Due to the unsaturated chemical structure of anthocyanins, these compounds are susceptible to reaction with molecular oxygen [135], causing their degradation either by a direct oxidative mechanism or by the action of oxidizing enzymes [136].

Figure 3b shows the analysis of variance, indicating that storage time did not significantly affect bulk density ($p > 0.05$), which could be explained by the fact that the blackberry powder did not absorb a high moisture content during storage [137]. As seen in Table 6, the moisture content only increased by 1% over the storage period. Although the change in water content in the powder was significant over time ($p < 0.05$), this increase in moisture content was not high enough to alter the bulk density of the product. As

Table 6 Effect of storage time (0, 15, 30, and 45 days) on some properties of blackberry powder

Days	Moisture	Aw	FRAP	ABTS	Anthocyanins	Bulk Density	Tapped Density	Solubility	Zinc	Folic Acid
	%		(μmol Trolox/g)	(μmol Trolox/g)	(mgcyanidin-3-glucoside/g)	(g/cm^3)	(g/cm^3)	%	(μg/100 g)	(μg/100 g)
0	2.071 a	0.298 a	18.47 a	10.02 a	0.310 a	0.382 a	0.62 a	91.966 a	209.0 a	122.65 a
0	1.95 a	0.298 a	17.98 a	9.91 a	0.570 a	0.373 a	0.624 a	92.409 a	211.0 a	122.63 a
0	1.978 a	0.306 a	20.39 a	9.93 a	0.600 a	0.374 a	0.622 a	91.396 a	207.0 a	122.58 a
15	2.306 b	0.33 b	13.21 b	6.78 b	0.230 a, b	0.392 a	0.633 a	90.816 a, b	195.0 b	105.28 b
15	2.306 b	0.341 b	11.37 b	6.04 b	0.469 a, b	0.373 a	0.63 a	89.743 a, b	198.0 b	105.29 b
15	2.306 b	0.347 b	12.65 b	6.07 b	0.356 a, b	0.366 a	0.622 a	91.199 a, b	192.0 b	105.27 b
30	2.889 c	0.338 b	9.829 c	5.92 b	0.256 b, c	0.385 a	0.619 a	87.127 a, b	184.0 c	104.22 c
30	2.85 c	0.343 b	8.957 c	5.99 b	0.159 b, c	0.367 a	0.629 a	90.663 a, b	186.0 c	104.19 c
30	2.931 c	0.349 b	8.444 c	5.96 b	0.186 b, c	0.374 a	0.621 a	88.399 a, b	182.0 c	104.2 c
45	3.012 d	0.372 c	6.087 d	4.31 c	0.110 c, d	0.384 a	0.629 a	81.67 b, c	144.6 d	90.93 d
45	2.963 d	0.372 c	6.225 d	4.35 c	0.085 c, d	0.381 a	0.63 a	88.067 b, c	145.1 d	90.95 d
45	3.011 d	0.373 c	6.362d	3.78 c	0.138 c, d	0.376 a	0.629 a	89.277 b, c	144.1 d	90.9 d

Different letters mean a significant difference ($p < 0.05$)

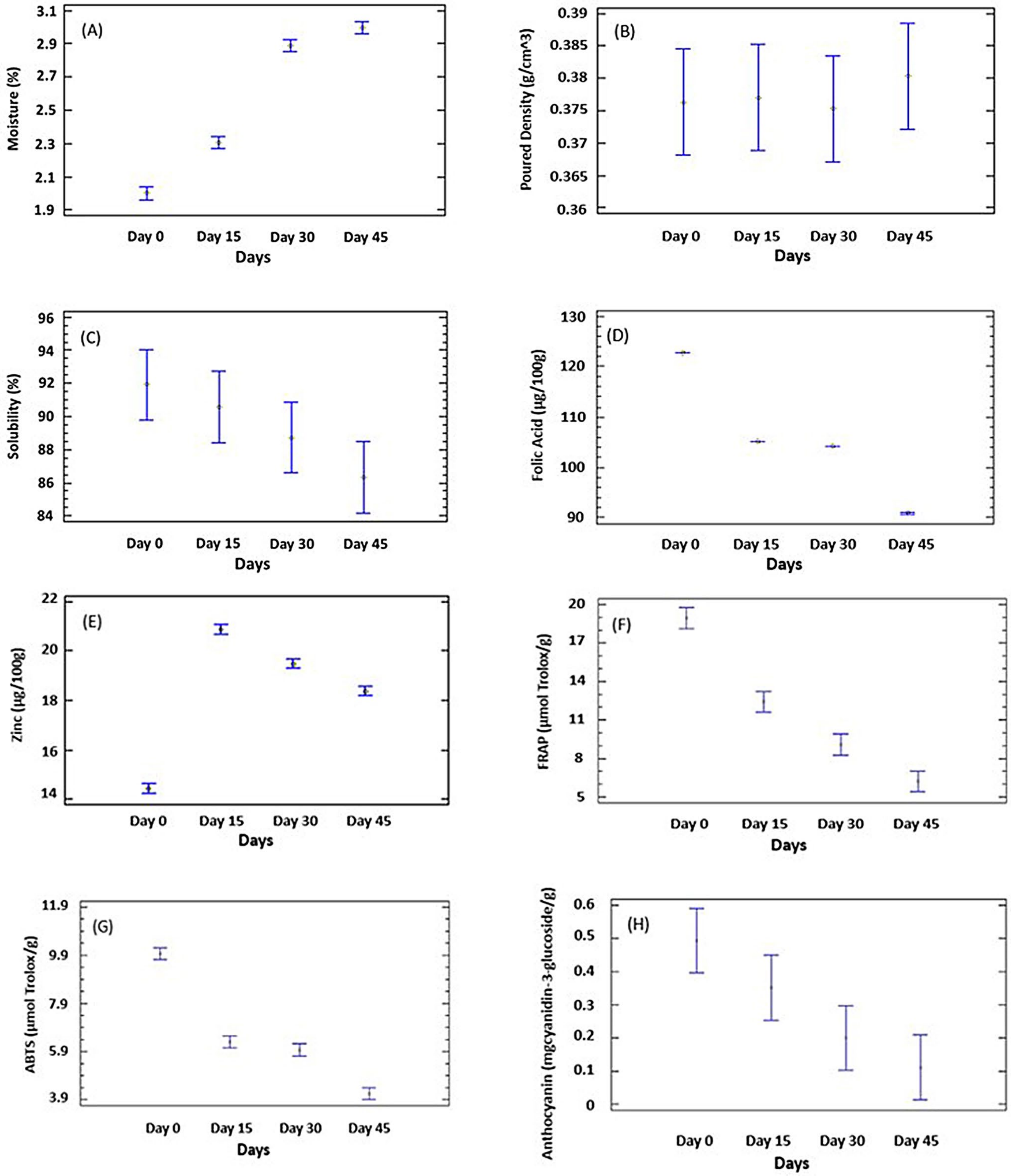

Fig. 3 Fisher LSD interval graphs with 95% confidence of the different variables analyzed, where: **(A)** Moisture, **(B)** poured density, **(C)** Solubility, **(D)** Folic acid, **(E)** Zinc, **(F)** Antioxidant-FRAP, **(G)** Antioxidant-ABTS, **(H)** Anthocyanin

reported by previous studies, high water absorption from the environment is necessary for significant changes in powder bulk densities [138]. Overall, the bulk density data are lower than those reported for jujube powders, which ranged between 0.47 and 0.63 g/ml [139]. Table 6 shows that bulk density data, are similar to those found for blackberry powders obtained by spray dry [140], cape gooseberry powders [141] and probiotic finger millet milk powder [138].

Although the solubility of the blackberry powder decreased over time, the obtained values indicate that it is a stable product with good solubility in water [142] and can be used for various food preparations [143]. Similar solubility changes over time have been seen in blackberry powders with *Lacticaseibacillus casei* ATCC393 [144] and in Amazonian fruit powders [143]. Figure 3C, shows that storage time significantly affected the solubility of the powder ($p < 0.05$), similar to findings by Chang et al. [145], who reported that storage time considerably decreased the solubility of guanabana powders. This behavior could be attributed to the tendency of blackberry powder to compact over time due to absorbed water, resulting in a decrease in solubility [145]. Additionally, Van der Waals forces lead to the formation of lumps that reduce the solubility of the powder [146].

The zinc content of the blackberry powder in Table 6 shows a significant time-dependent effect ($p < 0.05$), the zinc content decreases over time, Fig. 3E. This reduction can be explained by several reasons. First, spray drying using hot air can induce the formation of compounds such as ferric oxide [147], which is a zinc inhibitor. Second, zinc can also be lost due to its interactions with the moisture content of the powder or its reactions to food proteins and carbohydrates, which happens because zinc is a transition metal, deficient in electrons and forming stable complexes with the components of the food, whether proteins or carbohydrates, that are rich in electrons [148]. The formation of these complex systems can be accelerated by the moisture content of the product (which increases over time) since the moisture content of the food tends to hydrolyze zinc, thus increasing the interaction with proteins and carbohydrates due to the availability of ions [149]. Finally, blackberries contain phytate, which can bind zinc ions and potentially inhibit their availability [150]. The above-described complexes and reactions may precipitate zinc or form difficult-to-assimilate species, leading to the loss of effective zinc during storage.

Besides, the zinc content of the blackberry powder, as indicated in Table 6, fulfills over 20% of the recommended daily requirement, equivalent to 2.2 milligrams, in a 50-gram portion, in accordance with Resolution 810 of 2021 adopted by the Ministry of Health and Social Protection of Colombia. In this context, the powder product obtained here would provide nutritional support for both growing children and pregnant women.

In Fig. 3D, it can be observed that the folic acid content of blackberry powder decreased over time. The degradation of folic acid can be ascribed to multiple causes, including the presence of oxygen in the packing, ultraviolet light exposure, and the pH level of the blackberry powder [151]. The folic acid content was significantly affected by time, with a statistically significant impact ($p < 0.05$). Nevertheless, the folic acid levels found in this study meet 30% of the recommended daily intake, as stated in Resolution 810 of 2021 by the Ministry of Health and Social Protection of Colombia, for a serving size of 50 g.

Finally, the developed blackberry powder, shows properties like good water solubility that facilitate its consumption by dilution of 50 g in milk or water, or incorporated into healthy and protein shakes. The powdered product obtained also shows preserving of sensible compounds like antioxidants and folic acid, which would provide a nutritional contribution for both growing children and pregnant women.

Conclusion

This study could characterize the physicochemical properties of the blackberry grown in the town of Santa Elena, Medellín, Colombia, and obtain a blackberry powder enriched with zinc and folic acid by optimizing the spray drying process. The obtained blackberry powder guarantees 30% of the daily nutritional requirement of zinc and folate in 45 days of storage, both for growing children and pregnant women as stated in Resolution 810 of 2021 by the Ministry of Health and Social Protection of Colombia. This helps reach SDGs 2, 3, and 9.

Acknowledgements The authors would like to thank BIOALI Research group (Universidad de Antioquia), and the sustainability programs Research Groups Universidad de Antioquia 2023-2025-for Funding program ES84230027. The authors also thank CODI for funding the 2019-28618 project, corresponding to" Proyectos de Investigación Regionalización 2019" call for projects. The authors express their gratitude to: Andres Roman, Johan Franco, Fredy Amariles the coordinators and technicians of the laboratories on Universidad de Antioquia - Carmen de Viboral, Campus for the loan of spray drying equipment, pulpers, and refrigerators. A special thanks to Professor Ivan Dario Florez of the Centro de Multiliteracidades Escuela de Idiomas Universidad de Antioquia for his assistance in editing and improving the manuscript's English language.

Author Contributions Vargas-Marulanda Diego: Writing – Original Draft, Formal Analysis, Data Curation, Methodology.ValidationCastro-Tobon Santiago: Writing – Original Draft, Formal Analysis, Software, Graphic Elaboration.Vallejo-Marulanda Laura: Data Curation, Methodology. ValidationVanegas-Arboleda Valentina: Data Curation, Methodology, ValidationHenao-Gonzalez, Daniel: Writing – Original Draft, Formal analysis, Data Curation, Methodology.Validation, Gómez-Narváez Faver: Formal analysis, Data Curation, Methodology.

Project administration Funding acquisitionVega-Castro Oscar: Supervision, Conceptualization, Writing-Review, Investigation Funding acquisition and Software, Project administration.

Funding This research was funded by project 2019-28618-CODI, Universidad de Antioquia, corresponding to the call *"Proyectos de Investigación Regionalización 2019"*. Some reagents, supplies and trips to conferences, were financed by Project ES84230027 from the sustainability programs Research Groups Universidad de Antioquia 2023–2025.
Open Access funding provided by Colombia Consortium

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. FAO, F.I.D.A. OMS, PMA, and UNICEF, *El Estado De La Seguridad Alimentaria Y La nutrición en El Mundo 2021* (FAO, 2021). https://doi.org/10.4060/CB4474ES
2. UNICEF, Children, food and nutrition, 2019. [Online]. Available: https://www.unicef.org/media/60806/file/SOWC-2019.pdf
3. C. Fall, Fetal Malnutrition and Long-Term Outcomes, in Maternal and Child Nutrition: The First 1,000 Days., Nestlé Nutrition Institute Workshop, 2013. [Online]. Available: https://karger.com/books/book/198/chapter-abstract/5131371/Fetal-Malnutrition-and-Long-Term-Outcomes?redirectedFrom=fulltext
4. P.C. Papathakis, L.N. Singh, M.J. Manary, How maternal malnutrition affects linear growth and development in the offspring. Mol. Cell. Endocrinol. **435**, 40–47 (Aug. 2016). https://doi.org/10.1016/j.mce.2016.01.024
5. UNICEF, The State of the World's Children 1998, Aug. 1998. [Online]. Available: https://www.unicef.org/reports/state-worlds-children-1998
6. O.A. Ladipo, Nutrition in pregnancy: Mineral and Vitamin Supplements, American Journal of Clinical Nutrition, vol. 72, pp. 280S-290S, Aug. 2000, https://doi.org/10.1093/ajcn/72.1.280s
7. M.M. Black, Zinc deficiency and child development, Am J Clin Nutr, vol. 68, pp. 464S-469S, Aug. 1998, https://doi.org/10.1093/ajcn/68.2.464s
8. R. Zou et al., Maternal folate levels during pregnancy and offspring brain development in late childhood. Clin. Nutr. **40**, 3391–3400 (Aug. 2021). https://doi.org/10.1016/j.clnu.2020.11.025
9. K. Sahin, M. Elevli, Y. Paksoy, M. Koldas, The Rates of and relationship between Anemia and Deficiency of Iron, zinc, vitamin B12 and folic acid in hospitalized children. J. Pharm. Res. Int. 49–57 (Aug. 2021). https://doi.org/10.9734/jpri/2021/v33i27a31493
10. WHO, Daily iron and folic acid supplementation in pregnant women, 2016. [Online]. Available: https://iris.who.int/bitstream/handle/10665/77770/9789241501996_eng.pdf
11. Y. Shulpekova et al., The Concept of Folic Acid in Health and Disease. Molecules. **26**, 3731 (Aug. 2021). https://doi.org/10.3390/molecules26123731
12. S. Gupta, M. Brazier, N.M. Lowe, Zinc deficiency in low- and middle-income countries: prevalence and approaches for mitigation, Journal of Human Nutrition and Dietetics, vol. 33, pp. 624–643, Aug. 2020, https://doi.org/10.1111/jhn.12791
13. L. Widasari, M. Chalid, N. Jafar, A. Thaha, A. Dirpan, The Role of Multimicronutrients on Improving Better Pregnancy Outcomes: A literature review, Systematic Reviews in Pharmacy, vol. 11, pp. 550–553, 2020, [Online]. Available: https://pakdosen.unhas.ac.id/storage/dokumen/artikel-1682560146-17.%20The%20Role%20of%20Multimicronutrients%20on%20Improving.pdf
14. R. Wilson, J. Grieger, T. Bianco-Miotto, C. Roberts, Association between maternal zinc status, dietary zinc intake and pregnancy complications: a systematic review. Nutrients. **8**, 641 (Aug. 2016). https://doi.org/10.3390/nu8100641
15. K. Grzeszczak, S. Kwiatkowski, D. Kosik-Bogacka, The role of Fe, Zn, and Cu in pregnancy. Biomolecules. **10**, 1176 (Aug. 2020). https://doi.org/10.3390/biom10081176
16. K. Mandal, H. Lu, Zinc deficiency in children, International Journal of Science Inventions Today, vol. 6, pp. 9–19, 2017, [Online]. Available: http://www.ijsit.com/admin/ijsit_files/ZINC%20DEFICIENCY%20IN%20CHILDREN_IJSIT_6.1.2.pdf
17. K. Krishnaswamy, K.M. Nair, Importance of folate in human nutrition. Br. J. Nutr. **85**, S115–S124 (Aug. 2001). https://doi.org/10.1079/bjn2000303
18. S. Argyridis, Folic acid in pregnancy. Obstet. Gynaecol. Reprod. Med. **29**, 118–120 (Aug. 2019). https://doi.org/10.1016/j.ogrm.2019.01.008
19. Y. Ma, X. Shen, D. Zhang, The Relationship between Serum Zinc Level and Preeclampsia: A Meta-Analysis, Nutrients, vol. 7, pp. 7806–7820, Aug. 2015, https://doi.org/10.3390/nu7095366
20. R. Irwinda, S. Bardosono, A. Sungkar, N. Wibowo, Zinc, Beta-Carotene, and Vitamin D3 Supplementation and Placental IL-1β in Spontaneous Preterm Labor, *Researcher-app.com*, vol. 9, pp. 531–538, 2021, https://doi.org/10.12691/jfnr-9-10-5
21. M. Iqbal et al., Review on therapeutic and pharmaceutically important Medicinal Plant Asparagus officinalis L. J. Plant. Biochem. Physiol. **5** (2017). https://doi.org/10.4172/2329-9029.1000180
22. M. Johansson, M. Jägerstad, W. Frølich, Folates in lettuce: a pilot study. Food Nutr. Res. **51**, 22–30 (Aug. 2007). https://doi.org/10.3402/fnr.v51i1.1606
23. P. Maruvada et al., Aug., Knowledge gaps in understanding the metabolic and clinical effects of excess folates/folic acid: a summary, and perspectives, from an NIH workshop, American Journal of Clinical Nutrition, vol. 112, pp. 1390–1403, 2020, https://doi.org/10.1093/ajcn/nqaa259
24. A. Forouzesh, F. Forouzesh, S. Samadi Foroushani, A. Forouzesh, A New Method for calculating zinc content and determining appropriate zinc levels in Foods. SSRN Electron. J. Aug. (2022). https://doi.org/10.2139/ssrn.4133664
25. R. Wu, B. Frei, J.A. Kennedy, Y. Zhao, Effects of refrigerated storage and processing technologies on the bioactive compounds and antioxidant capacities of 'Marion' and 'Evergreen' blackberries, LWT, vol. 43, pp. 1253–1264, Aug. 2010, https://doi.org/10.1016/j.lwt.2010.04.002
26. A. Chis, C. Purcărea, N. Rotaru, D. Reste, *The Freezing Impact on Antioxidant Compounds of some Berries* (Animal Husbandry and Food Science and Technology, 2021)

27. F. Sabir, S. Ozcelik, A. Kucukbasmaci, Maintenance of postharvest quality of blackberry (Rubus fructicosus L.) fruits through salicylic acid and CaCl2 immersions, Acta Scientiarum Polonorum Hortorum Cultus, vol. 18, pp. 121–128, Aug. 2019, https://doi.org/10.24326/asphc.2019.4.11
28. R. Baltussen, C. Cile Knai, M. Sharan, Nutritional Epidemiology Iron Fortification and Iron Supplementation are cost-effective interventions to Reduce Iron Deficiency in four subregions of the World. Int. J. Nutr., **134**, 2004, doi: http://www.nutrition.org
29. O. Kahraman, Z. Ustunol, Effect of zinc fortification on Cheddar cheese quality. J. Dairy. Sci. **95**, 2840–2847 (Aug. 2012). https://doi.org/10.3168/jds.2011-4945
30. B. Tripathi, K. Platel, Finger millet (Eleucine coracana) flour as a vehicle for fortification with zinc. J. Trace Elem. Med Biol. **24**, 46–51 (Aug. 2010). https://doi.org/10.1016/j.jtemb.2009.09.001
31. D. Sun-Waterhouse, G. Waterhouse, Spray-drying of Green or Gold Kiwifruit juice–milk mixtures; novel formulations and processes to Retain Natural Fruit Colour and antioxidants. Food Bioproc Tech. **8**, 191–207 (Aug. 2014). https://doi.org/10.1007/s11947-014-1397-4
32. M. Scorsatto, S.K. Uehara, R.R. Luiz, G.M.M. de Oliveira, G. Rosa, Fortification of flours with folic acid reduces homocysteine levels in Brazilian women. Nutr. Res. **31**, 889–895 (Aug. 2011). https://doi.org/10.1016/j.nutres.2011.10.003
33. C. Peña Correa, R. Fabiola, M. Cortés Rodríguez, H. Gil, Estabilidad Fisicoquímica y Funcional de Uchuva (Physalis peruviana L.) Impregnada a Vacío con Calcio y Vitaminas B9, D y E, Durante el Almacenamiento Refrigerado, *Rev Fac Nac Agron Medellin*, vol. 66, pp. 6929–6938, 2024, [Online]. Available: http://www.redalyc.org/articulo.oa?id=179928411010
34. M. Ruiz-Rico, É. Pérez-Esteve, M.J. Lerma-García, M.D. Marcos, R. Martínez-Máñez, J.M. Barat, Protection of folic acid through encapsulation in mesoporous silica particles included in fruit juices, *Food Chem*, vol. 218, pp. 471–478, Aug. 2017, https://doi.org/10.1016/j.foodchem.2016.09.097
35. S. Pérez Prieto, B. Cancho Grande, S. García Falcón, J. Simal Gándara, Screening for folic acid content in vitamin-fortified beverages. Food Control. **17**, 900–904 (Aug. 2006). https://doi.org/10.1016/j.foodcont.2005.06.009
36. T. Kolarević et al., Aug., Phenolic Compounds and Antioxidant Properties of Field-Grown and In Vitro Leaves, and Calluses in Blackberry and Blueberry, Horticulturae, vol. 7, p. 420, 2021, https://doi.org/10.3390/horticulturae7110420
37. L.J. Bernal, L.A. Melo, C. Díaz Moreno, Evaluation of the Antioxidant Properties and Aromatic Profile During Maturation of The Blackberry (Rubus glaucus Benth) and The Bilberry (Vaccinium meridionale Swartz), Rev Fac Nac Agron Medellin, vol. 67, pp. 7209–7218, Aug. 2014, https://doi.org/10.15446/rfnam.v67n1.42649
38. D.P. Moraes et al., Influence of the cultivar on the composition of blackberry (Rubus spp.) minerals. J. Food Compos. Anal. **100**, 103913 (Aug. 2021). https://doi.org/10.1016/j.jfca.2021.103913
39. R.T. Threlfall et al., Physiochemical and sensory attributes of fresh blackberries grown in the Southeastern United States. HortScience. **51**, 1351–1362 (Aug. 2016). https://doi.org/10.21273/hortsci10678-16
40. G. Franco, M.C. García, G. Antia, J. Henao, Cosecha y manejo poscosecha, 2020, *Corporación colombiana de investigación agropecuaria - AGROSAVIA*. doi: http://hdl.handle.net/20.500.12324/36642
41. A. López, Manual for the preparation and sale of fruits and vegetables, 2002, FAO. [Online]. Available: https://openknowledge.fao.org/server/api/core/bitstreams/a455dae2-6d9a-49a2-8e97-e0e85b5dac8d/content
42. W. ALBARRACÍN, APLICACIÓN Y EFECTO DE UN RECUBRIMIENTO COMESTIBLE SOBRE LA VIDA ÚTIL DE, LA MORA DE CASTILLA (RUBUS GLAUCUS BENTH), Revista Vitae. **23**, 202–209 (Aug. 2016). https://doi.org/10.17533/udea.vitae.v23n3a06
43. A. Schiavon, G. Leivas, E. Delazeri, A. Alves, P. Mello-Farias, L. Antunes, Physical-chemical characteristics of 'Tupy' blackberry harvested at different ripening stages and kept under refrigeration, 2021, https://doi.org/10.3/JQUERY-UI.JS
44. C. Türkben, E. Sarıburun, C. Demir, V. Uylaşer, Effect of freezing and frozen Storage on Phenolic compounds of Raspberry and Blackberry cultivars. Food Anal. Methods. **3**, 144–153 (Aug. 2009). https://doi.org/10.1007/s12161-009-9102-3
45. M. Kaveh, E. Taghinezhad, M. Aziz, Effects of physical and chemical pretreatments on drying and quality properties of blackberry (Rubus spp.) in hot air dryer, Food Sci Nutr, vol. 8, pp. 3843–3856, Aug. 2020, https://doi.org/10.1002/fsn3.1678
46. G. Azofeifa, S. Quesada, A.M. Pérez, F. Vaillant, A. Michel, Pasteurization of blackberry juice preserves polyphenol-dependent inhibition for lipid peroxidation and intracellular radicals. J. Food Compos. Anal. **42**, 56–62 (Aug. 2015). https://doi.org/10.1016/j.jfca.2015.01.015
47. B. Pérez-Grijalba et al., Biofunctionality, Colorimetric coefficients and Microbiological Stability of Blackberry (Rubus Fructicosus Var. Himalaya) Juice under Microwave/Ultrasound Processing. Rev. Mex Ing. Quim. **17**, 13–28 (2018). https://doi.org/10.24275/10.24275/uam/izt/dcbi/revmexingquim/2018v17n1/perez
48. Z. Tarakçı, M. Durak, Investigation of the Chemical, textural and sensory properties of some Fruit Puree added ice cream. J. Nutr. Fasten Health Aug. (2020). https://doi.org/10.22038/jnfh.2020.52696.1302
49. M.-A. Poiana, M.-F. Munteanu, D.-M. Bordean, R. Gligor, E. Alexa, Assessing the effects of different pectins addition on color quality and antioxidant properties of blackberry jam. Chem. Cent. J. **7**, 121 (Aug. 2013). https://doi.org/10.1186/1752-153X-7-121
50. S.J.D. Jaeschke, G. Mercali, I. Tessaro, L. Marczak, Degradation kinetics of anthocyanins in blackberry pulp during ohmic and conventional heating, Int Food Res J, vol. 26, p. 87, Aug. 2019, doi
51. S. Alemán, E. Pacheco-Delahaye, E. Pérez, M. Schroeder, Elaboration of blackberry (Rubus glaucus Benth.) jellies with native and modified banana starches (Musa ABB), African Journal of Food Science, vol. 5, pp. 181–187, 2011, [Online]. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e355d7f5eda62f929c564a25b126389bf1521c3b
52. E. Wong, F. Vaillant, A. Pérez, Osmosonication of Blackberry Juice: impact on selected pathogens, Spoilage Microorganisms, and Main Quality parameters. J. Food Sci. **75**, M468–M474 (Aug. 2010). https://doi.org/10.1111/j.1750-3841.2010.01730.x
53. J. Osorio-Arias et al., New powder material obtained from spent coffee ground and whey protein; thermal and morphological analysis. Mater. Chem. Phys. **240**, 122171 (Aug. 2020). https://doi.org/10.1016/j.matchemphys.2019.122171
54. E.J. Crosby, Spray drying handbook, Drying Technology, vol. 7, pp. 419–425, Aug. 1989, https://doi.org/10.1080/07373938908916598
55. S. Nath, G.R. Satpathy, A systematic approach for investigation of spray drying processes, Drying Technology, vol. 16, pp. 1173–1193, Aug. 1998, https://doi.org/10.1080/07373939808917459
56. A. Lechanteur, B. Evrard, Influence of Composition and Spray-Drying Process Parameters on Carrier-Free DPI Properties and Behaviors in the Lung: A review, *Pharmaceutics*, vol. 12, p. 55, Aug. 2020, https://doi.org/10.3390/pharmaceutics12010055
57. K.O. Iwuozor, A.G. Adeniyi, E.C. Emenike, M.I. Adepoju, M.O. Ahmed, Sugarcane Juice Powder Produced from Spray Drying Technology: A Review of Properties and Operating Parameters,

Sugar Tech, Aug. 2022, https://doi.org/10.1007/s12355-022-01211-6
58. M.R.I. Shishir, W. Chen, Trends of spray drying: a critical review on drying of fruit and vegetable juices. Trends Food Sci. Technol. **65**, 49–67 (Aug. 2017). https://doi.org/10.1016/j.tifs.2017.05.006
59. D. Borrmann, A.P.T.R. Pierucci, S.G.F. Leite, M.H.M. Leão, Microencapsulation of passion fruit (Passiflora) juice with n-octenylsuccinate-derivatised starch using spray-drying, Food and Bioproducts Processing, vol. 91, pp. 23–27, Aug. 2013, https://doi.org/10.1016/j.fbp.2012.08.001
60. D. Krishnaiah, A. Bono, R. Sarbatly, R. Nithyanandam, S.M. Anisuzzaman, Optimisation of spray drying operating conditions of Morinda citrifolia L. fruit extract using response surface methodology. J. King Saud Univ. - Eng. Sci. **27**, 26–36 (Aug. 2015). https://doi.org/10.1016/j.jksues.2012.10.004
61. S. Santhalakshmy, S.J. Don Bosco, S. Francis, M. Sabeena, Effect of inlet temperature on physicochemical properties of spray-dried jamun fruit juice powder. Powder Technol. **274**, 37–43 (Aug. 2015). https://doi.org/10.1016/j.powtec.2015.01.016
62. L.D. Daza, A. Fujita, M. Lacroix, J. Neves, A.S. Sant'Ana, M.I. Genovese, Aug., Effect of spray drying conditions on the physical properties of Cagaita (Eugenia Dysenterica DC.) Fruit extracts, **97**, pp. 20–29, 2016, https://doi.org/10.1016/j.fbp.2015.10.001
63. T.C. Kha, M.H. Nguyen, P.D. Roach, Effects of spray drying conditions on the physicochemical and antioxidant properties of the Gac (Momordica cochinchinensis) fruit aril powder, J Food Eng, vol. 98, pp. 385–392, Aug. 2010, https://doi.org/10.1016/j.jfoodeng.2010.01.016
64. V. Patil, A.K. Chauhan, R.P. Singh, Optimization of the spray-drying process for developing guava powder using response surface methodology. Powder Technol. **253**, 230–236 (Aug. 2014). https://doi.org/10.1016/j.powtec.2013.11.033
65. G. Giraldo-Gomez, C. Orrego-Alzate, L. Grajales, V. Telis, A. Gabas, J. Telis-Romero, Effect of drying methods on the thermodynamic properties of blackberry pulp powder, Dyna (Medellin), vol. 78, pp. 139–148, 2011, [Online]. Available: http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0012-73532011000400017
66. C. Ferrari, S. Germer, J. de Aguirre, Effects of Spray-Drying conditions on the Physicochemical properties of Blackberry Powder. Drying Technol. **30**, 154–163 (2012). 10.108007373937.2011.628429
67. M. Braga, S.C. Rocha, M.D. Hubinger, Spray-Drying of Milk–Blackberry Pulp Mixture: Effect of Carrier Agent on the Physical Properties of Powder, Water Sorption, and Glass Transition Temperature, J Food Sci, vol. 83, pp. 1650–1659, Aug. 2018, https://doi.org/10.1111/1750-3841.14187
68. J.A. Eldridge, D. Repko, R.J. Mumper, Retention of Polyphenolic Species in Spray-Dried Blackberry Extract Using Mannitol as a Thermoprotectant, J Med Food, vol. 17, pp. 1064–1069, Aug. 2014, https://doi.org/10.1089/jmf.2013.0177
69. F. Weber, K. Boch, A. Schieber, Influence of copigmentation on the stability of spray dried anthocyanins from blackberry, LWT, vol. 75, pp. 72–77, Aug. 2017, https://doi.org/10.1016/j.lwt.2016.08.042
70. C.C. Ferrari, S.P.M. Germer, I.D. Alvim, F.Z. Vissotto, J.M. de Aguirre, Influence of carrier agents on the physicochemical properties of blackberry powder produced by spray drying. Int. J. Food Sci. Technol. **47**, 1237–1245 (Aug. 2012). https://doi.org/10.1111/j.1365-2621.2012.02964.x
71. B.N. Estevinho, I. Carlan, A. Blaga, F. Rocha, Soluble vitamins (vitamin B12 and vitamin C) microencapsulated with different biopolymers by a spray drying process. Powder Technol. **289**, 71–78 (Aug. 2016). https://doi.org/10.1016/j.powtec.2015.11.019
72. R.T. Rigon, C.P. Zapata, Noreña, Microencapsulation by spray-drying of bioactive compounds extracted from blackberry (rubus fruticosus). J. Food Sci. Technol. **53**, 1515–1524 (Aug. 2016). https://doi.org/10.1007/s13197-015-2111-x
73. F.R. Abrahão et al., Aug., Microencapsulation of bioactive compounds from espresso spent coffee by spray drying, **103**, pp. 116–124, 2019, https://doi.org/10.1016/j.lwt.2018.12.061
74. Y. Ramakrishnan, N.M. Adzahan, Y.A. Yusof, K. Muhammad, Effect of wall materials on the spray drying efficiency, powder properties and stability of bioactive compounds in tamarillo juice microencapsulation. Powder Technol. **328**, 406–414 (Aug. 2018). https://doi.org/10.1016/j.powtec.2017.12.018
75. A.M. Serpa-Guerra, J.A. Velásquez-Cock, J.A. Barajas-Gamboa, L.M. Vélez-Acosta, B. Gómez-Hoyos, R. Zuluaga-Gallego, Development of a fortified drink from the mixture of small colombian native fruits, Dyna (Medellin), vol. 85, pp. 185–193, Aug. 2018, https://doi.org/10.15446/dyna.v85n204.67548
76. M. Kopjar, I. Ćorković, I. Buljeta, J. Šimunović, A. Pichler, Fortification of Pectin/Blackberry hydrogels with Apple fibers: Effect on Phenolics, antioxidant activity and inhibition of α-Glucosidase. Antioxidants. **11**, 1459 (Aug. 2022). https://doi.org/10.3390/antiox11081459
77. A. Fernandes et al., Blackberry anthocyanins: β-Cyclodextrin fortification for thermal and gastrointestinal stabilization. Food Chem. **245**, 426–431 (Aug. 2018). https://doi.org/10.1016/j.foodchem.2017.10.109
78. N. Betoret, E. Pérez, C. Barrera, M. Castelló, Operaciones auxiliares de limpieza y desinfección en la industria agroalimentaria, 2021. doi: http://hdl.handle.net/10251/165529
79. AOAC, *Official Method of Analysis of AOAC Intl*, 17th edn. (Association of Official Analytical Chemists, Gaithersburg, MD, USA, 2003)
80. O. Vega-Castro et al., Characterization and production of a polyhydroxyalkanoate from Cassava Peel Waste: manufacture of Biopolymer microfibers by Electrospinning. J. Polym. Environ. **29**, 187–200 (Aug. 2020). https://doi.org/10.1007/s10924-020-01861-1
81. L.P. Pui, R. Karim, Y.A. Yusof, C.W. Wong, H.M. Ghazali, Optimization of spray-drying parameters for the production of 'Cempedak' (Artocarpus integer) fruit powder, Journal of Food Measurement and Characterization, vol. 14, pp. 3238–3249, Aug. 2020, https://doi.org/10.1007/s11694-020-00565-3
82. G. Ferreira Nogueira, F.M. Fakhouri, R.A. de Oliveira, Incorporation of spray dried and freeze dried blackberry particles in edible films: morphology, stability to pH, sterilization and biodegradation. Food Packag Shelf Life. **20**, 100313 (Aug. 2019). https://doi.org/10.1016/j.fpsl.2019.100313
83. R. Pérez-Masiá, R. López-Nicolás, M.J. Periago, G. Ros, J.M. Lagaron, A. López-Rubio, Encapsulation of folic acid in food hydrocolloids through nanospray drying and electrospraying for nutraceutical applications. Food Chem. **168**, 124–133 (Aug. 2015). https://doi.org/10.1016/j.foodchem.2014.07.051
84. C. Leyva-Porras et al., Strawberry Juice powders: Effect of Spray-Drying conditions on the Microencapsulation of Bioactive Components and Physicochemical Properties. Molecules. **26**, 5466 (Aug. 2021). https://doi.org/10.3390/molecules26185466
85. Z. Gong, M. Yu, W. Wang, X. Shi, Functionality of spray-dried strawberry powder: effects of whey protein isolate and maltodextrin. Int. J. Food Prop. **21**, 2229–2238 (Aug. 2018). https://doi.org/10.1080/10942912.2018.1506477
86. D. Henao-González, D. David, J. Torres-Oquendo, P. Saboral, O. Vega-Castro, Design and Optimization of a Strawberry-Based Dispersion to Produce a Spray Drying Functional Powdered Product, Fortified with Folic Acid and Zinc., *Food and Bioproducts Processing*, Aug. 2024, https://doi.org/10.1016/j.fbp.2024.05.017
87. K. Muzaffar, P. Kumar, Comparative efficiency of maltodextrin and protein in the production of spray-dried tamarind pulp

powder. Drying Technol. **34**, 802–809 (Aug. 2015). https://doi.org/10.1080/07373937.2015.1080724

88. J. Contreras-Calderón, L. Calderón-Jaimes, E. Guerra-Hernández, B. García-Villanova, Antioxidant capacity, phenolic content and vitamin C in pulp, peel and seed from 24 exotic fruits from Colombia. Food Res. Int. **44**, 2047–2053 (Aug. 2011). https://doi.org/10.1016/j.foodres.2010.11.003
89. J. Osorio-Arias et al., Sustainable management and valorization of spent Coffee grounds through the optimization of thin layer Hot Air-Drying process. Waste Biomass Valorization. **11**, 5015–5026 (Aug. 2019). https://doi.org/10.1007/s12649-019-00793-9
90. W. Brand-Williams, M.E. Cuvelier, C. Berset, Use of a free Radical Method to evaluate antioxidant activity. LWT - Food Sci. Technol. **28**, 25–30 (Aug. 1995). https://doi.org/10.1016/s0023-6438(95)80008-5
91. L. Cardona, G. Cabrera, Estudio de la fotodegradación de ácido fólico encapsulado en microesferas de goma arábiga y maltodextrina, *Revista Cubana de Farmacia*, vol. 44, pp. 443–455, 2024, [Online]. Available: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0034-75152010000400003
92. M.J. Akhtar, M.A. Khan, I. Ahmad, High performance liquid chromatographic determination of folic acid and its photodegradation products in the presence of riboflavin, J Pharm Biomed Anal, vol. 16, pp. 95–99, Aug. 1997, https://doi.org/10.1016/s0731-7085(96)02028-6
93. A. Cherfi, S. Abdoun, O. Gaci, Food survey: levels and potential health risks of chromium, lead, zinc and copper content in fruits and vegetables consumed in Algeria. Food Chem. Toxicol. **70**, 48–53 (Aug. 2014). https://doi.org/10.1016/j.fct.2014.04.044
94. C.S. Cuesta-Riaño, M.P. Castro-Guascaa, M.P. Tarazona-Díaz, Anthocyanin Extract from Blackberry Used as an Indicator of Hydrogen Potential, International Journal of Fruit Science, vol. 22, pp. 224–234, Aug. 2022, https://doi.org/10.1080/15538362.2022.2037036
95. R. Sáez-Hernández, P. Ruiz, A.R. Mauri-Aucejo, V. Yusa, M.L. Cervera, Determination of acrylamide in toasts using digital image colorimetry by smartphone. Food Control. **141**, 109163 (Aug. 2022). https://doi.org/10.1016/j.foodcont.2022.109163
96. M.C. Melo-Guerrero, D.E. Ortiz-Jurado, A.M. Hurtado-Benavides, M.C. Melo-Guerrero, D.E. Ortiz-Jurado, A.M. Hurtado-Benavides, Comparación de la composición y de la actividad antioxidante del aceite esencial de manzanilla (Matricaria chamomilla L.) obtenido mediante extracción con fluidos supercríticos y otras técnicas verdes, *Rev Acad Colomb Cienc Exactas Fis Nat*, vol. 44, pp. 845–856, Aug. 2020, https://doi.org/10.18257/raccefyn.862
97. R.V. Tonon, C.R.F. Grosso, M.D. Hubinger, Influence of emulsion composition and inlet air temperature on the microencapsulation of flaxseed oil by spray drying. Food Res. Int. **44**, 282–289 (Aug. 2011). https://doi.org/10.1016/j.foodres.2010.10.018
98. J. Saavedra et al., Industrial Avocado waste: functional compounds preservation by convective drying process. J. Food Eng. **198**, 81–90 (Aug. 2017). https://doi.org/10.1016/j.jfoodeng.2016.11.018
99. N.M.A. Hassimotto, R.V. da Mota, B.R. Cordenunsi, F.M. Lajolo, Physico-chemical characterization and bioactive compounds of blackberry fruits (Rubus sp.) grown in Brazil, Food Science and Technology, vol. 28, pp. 702–708, Aug. 2008, https://doi.org/10.1590/S0101-20612008000300029
100. D. Cárdenas, W.A. Cardona, J. Ruiz, M. Marina, Relationship between variable doses of N, P, K and ca and the physicochemical and proximal characteristics of andean blackberry (Rubus glaucus Benth). Sci. Hortic. **256**, 108528 (Aug. 2019). https://doi.org/10.1016/j.scienta.2019.05.055
101. J.C.P. Pombo, H. de Madeiros, S. Pena, Optimization of the spray drying process for developing cupuassu powder. J. Food Sci. Technol. **57**, 4501–4513 (Aug. 2020). https://doi.org/10.1007/s13197-020-04487-2
102. J.-H. Kim, J.H. Kim, J.-B. Eun, Optimization of spray drying process parameters for production of Japanese apricot (Prunus mume Sieb. et Zucc.) juice powder, Food Sci Biotechnol, vol. 30, pp. 1075–1086, Aug. 2021, https://doi.org/10.1007/s10068-021-00950-8
103. V.S. Farias-Cervantes, A. Chávez-Rodríguez, P.A. García-Salcedo, P.M. García-López, J. Casas-Solís, I. Andrade-González, Antimicrobial effect and in vitro release of anthocyanins from berries and Roselle obtained via microencapsulation by spray drying. J. Food Process. Preserv. **42**, e13713–e13713 (Aug. 2018). https://doi.org/10.1111/jfpp.13713
104. X. Chen et al., Comparing three types of Mandarin Powders Prepared via Microfluidic-Jet Spray Drying: physical properties, Phenolic Retention and volatile profiling. Foods. **10**, 123 (Aug. 2021). https://doi.org/10.3390/foods10010123
105. J. Guerin et al., Lactobacillus rhamnosus GG encapsulation by spray-drying: milk proteins clotting control to produce innovative matrices. J. Food Eng. **193**, 10–19 (Aug. 2017). https://doi.org/10.1016/j.jfoodeng.2016.08.008
106. J. Nishad, C.J. Selvan, S.A. Mir, S.J.D. Bosco, Effect of spray drying on physical properties of sugarcane juice powder (Saccharum officinarum L). J. Food Sci. Technol. **54**, 687–697 (Aug. 2017). https://doi.org/10.1007/s13197-017-2507-x
107. S.Y. Quek, N.K. Chok, P. Swedlund, The physicochemical properties of spray-dried watermelon powders. Chem. Eng. Process. **46**, 386–392 (Aug. 2007). https://doi.org/10.1016/j.cep.2006.06.020
108. A.P. Da Fonseca, Encapsulation of anthocyanin-rich extract from blackberry residues by spray-drying, freeze-drying and supercritical antisolvent. Powder Technol. **340**, 553–562 (Aug. 2018). https://doi.org/10.1016/j.powtec.2018.09.063
109. K. Thaipong, U. Boonprakob, K. Crosby, L. Cisneros-Zevallos, D. Hawkins Byrne, Comparison of ABTS, DPPH, FRAP, and ORAC assays for estimating antioxidant activity from guava fruit extracts, Journal of Food Composition and Analysis, vol. 19, pp. 669–675, Aug. 2006, https://doi.org/10.1016/j.jfca.2006.01.003
110. S.B. Araujo-Díaz, C. Leyva-Porras, P. Aguirre-Bañuelos, C. Álvarez-Salas, Z. Saavedra-Leos, Evaluation of the physical properties and conservation of the antioxidants content, employing inulin and maltodextrin in the spray drying of blueberry juice, Carbohydr Polym, vol. 167, pp. 317–325, Aug. 2017, https://doi.org/10.1016/j.carbpol.2017.03.065
111. P. Mishra, S. Mishra, C.L. Mahanta, Effect of maltodextrin concentration and inlet temperature during spray drying on physicochemical and antioxidant properties of amla (Emblica officinalis) juice powder. Food Bioprod. Process. **92**, 252–258 (Aug. 2014). https://doi.org/10.1016/j.fbp.2013.08.003
112. D.P.S. Oberoi, D.S. Sogi, Effect of drying methods and maltodextrin concentration on pigment content of watermelon juice powder. J. Food Eng. **165**, 172–178 (Aug. 2015). https://doi.org/10.1016/j.jfoodeng.2015.06.024
113. S.M. Jafari, M.G. Ghalenoei, D. Dehnad, Influence of spray drying on water solubility index, apparent density, and anthocyanin content of pomegranate juice powder. Powder Technol. **311**, 59–65 (Aug. 2017). https://doi.org/10.1016/j.powtec.2017.01.070
114. M.P. Zia, I. Alibas, Influence of the drying methods on color, vitamin C, anthocyanin, phenolic compounds, antioxidant activity, and in vitro bioaccessibility of blueberry fruits. Food Biosci. **42**, 101179 (Aug. 2021). https://doi.org/10.1016/j.fbio.2021.101179
115. H. Pashazadeh, A. Ali Redha, I. Koca, Effect of convective drying on phenolic acid, flavonoid and anthocyanin content, texture and microstructure of black rosehip fruit. J. Food Compos. Anal. **125**, 105738 (Aug. 2024). https://doi.org/10.1016/j.jfca.2023.105738
116. S. Kittibunchakul, P. Temviriyanukul, P. Chaikham, V. Kemsawasd, Effects of freeze drying and convective hot-air drying on

predominant bioactive compounds, antioxidant potential and safe consumption of maoberry fruits. LWT. **184**, 114992 (Aug. 2023). https://doi.org/10.1016/j.lwt.2023.114992

117. M. Fazaeli, Z. Emam-Djomeh, A. Kalbasi Ashtari, M. Omid, Effect of spray drying conditions and feed composition on the physical properties of black mulberry juice powder. Food Bioprod. Process. **90**, 667–675 (Aug. 2012). https://doi.org/10.1016/j.fbp.2012.04.006
118. R. Sasikumar, M. Das, S.C. Deka, Process optimization for the production of blood fruit powder by spray drying technique and its quality evaluation, J Food Sci Technol, vol. 57, pp. 2269–2282, Aug. 2020, https://doi.org/10.1007/s13197-020-04264-1
119. L. Serna-Cock, C. Torres-León, A. Ayala-Aponte, Evaluación De Polvos Alimentarios Obtenidos De Cáscaras De Mango (Mangifera indica) como fuente de ingredientes funcionales. Información tecnológica. **26**, 41–50 (2015). https://doi.org/10.4067/s0718-07642015000200006
120. C. Godswill, V. Somtochukwu, C. Kate, The functional properties of foods and flours, *International Journal of Advanced Academic Research | Sciences*, vol. 5, pp. 2488–9849, 2019, [Online]. Available: https://www.ijaar.org/articles/Volume5-Number11/Sciences-Technology-Engineering/ijaar-ste-v5n11-nov19-p16.pdf
121. N. Kingwatee, A. Apichartsrangkoon, P. Chaikham, S. Worametrachanon, J. Techarung, T. Pankasemsuk, Spray drying Lactobacillus casei 01 in lychee juice varied carrier materials, *Lebensmittel-Wissenschaft & Technologie*, vol. 62, pp. 847–853, Aug. 2015, https://doi.org/10.1016/j.lwt.2014.12.007
122. H. Gutierrez, *Análisis Y diseño de experimentos*, 2nd edn. (McGRAW-HILL/INTERAMERICANA EDITORES, México, 2008)
123. P. Galaz, M. Valdenegro, C. Ramírez, H. Nuñez, S. Almonacid, R. Simpson, Effect of drum drying temperature on drying kinetic and polyphenol contents in pomegranate peel. J. Food Eng. **208**, 19–27 (Aug. 2017). https://doi.org/10.1016/j.jfoodeng.2017.04.002
124. R. Santiago-Adame et al., Spray drying-microencapsulation of cinnamon infusions (Cinnamomum zeylanicum) with maltodextrin. LWT - Food Sci. Technol. **64**, 571–577 (Aug. 2015). https://doi.org/10.1016/j.lwt.2015.06.020
125. R.V. Tonon, C. Brabet, D. Pallet, P. Brat, M.D. Hubinger, Physicochemical and morphological characterisation of açai (Euterpe Oleraceae Mart.) Powder produced with different carrier agents. Int. J. Food Sci. Technol. **44**, 1950–1958 (Aug. 2009). https://doi.org/10.1111/j.1365-2621.2009.02012.x
126. J.A. Grabowski, V.-D. Truong, C.R. Daubert, Spray-drying of Amylase Hydrolyzed Sweetpotato Puree and Physicochemical properties of Powder. J. Food Sci. **71**, E209–E217 (Aug. 2006). https://doi.org/10.1111/j.1750-3841.2006.00036.x
127. M. Cano-Chauca, P.C. Stringheta, A.M. Ramos, J. Cal-Vidal, Effect of the carriers on the microstructure of mango powder obtained by spray drying and its functional characterization, Innovative Food Science & Emerging Technologies, vol. 6, pp. 420–428, Aug. 2005, https://doi.org/10.1016/j.ifset.2005.05.003
128. K. Sarabandi, S.M. Jafari, A.S. Mahoonak, A. Mohammadi, Application of gum Arabic and maltodextrin for encapsulation of eggplant peel extract as a natural antioxidant and color source, Int J Biol Macromol, vol. 140, pp. 59–68, Aug. 2019, https://doi.org/10.1016/j.ijbiomac.2019.08.133
129. N.S. Wei, R. Sulaiman, Effect of Maltodextrin, Arabic Gum, and Beetroot Juice Concentration on the Powder Properties of Spray-Dried Beetroot-Skim Milk Mixtures, *Acta Universitatis Cibiniensis. Series E: Food Technology*, vol. 26, pp. 209–224, Aug. 2022, https://doi.org/10.2478/aucft-2022-0017
130. K. Vivek, S. Mishra, R.C. Pradhan, Characterization of spray dried probiotic Sohiong fruit powder with Lactobacillus plantarum. LWT. **117**, 108699 (Aug. 2020). https://doi.org/10.1016/j.lwt.2019.108699
131. S.N. Bhusari, K. Muzaffar, P. Kumar, Effect of carrier agents on physical and microstructural properties of spray dried tamarind pulp powder. Powder Technol. **266**, 354–364 (Aug. 2014). https://doi.org/10.1016/j.powtec.2014.06.038
132. S. Ersus, U. Yurdagel, Microencapsulation of anthocyanin pigments of black carrot (Daucus carota L.) by spray drier. J. Food Eng. **80**, 805–812 (Aug. 2007). https://doi.org/10.1016/j.jfoodeng.2006.07.009
133. Z. Fang, B. Bhandari, Effect of spray drying and storage on the stability of bayberry polyphenols. Food Chem. **129**, 1139–1147 (Aug. 2011). https://doi.org/10.1016/j.foodchem.2011.05.093
134. R.J. Sharma, R.C. Gupta, S. Singh, A.K. Bansal, I.P. Singh, Stability of anthocyanins- and anthocyanidins-enriched extracts, and formulations of fruit pulp of Eugenia jambolana ('jamun'). Food Chem. **190**, 808–817 (Aug. 2016). https://doi.org/10.1016/j.foodchem.2015.06.029
135. Z.E. Sikorski, Fennema's Food Chemistry (Fifth Edition) Edited by SrinivasanDamodaranKirk L.Parkin CRC Press, B. Raton, Florida, 2017. 1107 pp. ISBN 9781482208122., *J Food Biochem*, vol. 42, p. e12483, Aug. 2018, https://doi.org/10.1111/jfbc.12483
136. A. Patras, N.P. Brunton, C. O'Donnell, B.K. Tiwari, Effect of thermal processing on anthocyanin stability in foods; mechanisms and kinetics of degradation. Trends Food Sci. Technol. **21**, 3–11 (Aug. 2010). https://doi.org/10.1016/j.tifs.2009.07.004
137. J.G.V.B.-C. Enrique, O.-R. Pablo, Food Powders: Physical Properties, Processing, and Functionality, no. 1. 2014. https://doi.org/10.1007/s13398-014-0173-7.2
138. S. Yadav, S. Mishra, Moisture sorption isotherms and storage study of spray-dried probiotic finger millet milk powder. J. Stored Prod. Res. **102**, 102128 (Aug. 2023). https://doi.org/10.1016/j.jspr.2023.102128
139. X. Xia et al., Effect of jujube kernel powder addition on moisture absorption performance, color stability, texture properties and agglomeration characteristics of jujube powder. LWT. **174**, 114452 (Aug. 2023). https://doi.org/10.1016/j.lwt.2023.114452
140. L. Franceschinis, D.M. Salvatori, N. Sosa, C. Schebor, Physical and Functional Properties of Blackberry Freeze- and Spray-Dried Powders, Drying Technology, vol. 32, pp. 197–207, Aug. 2013, https://doi.org/10.1080/07373937.2013.814664
141. C.-A. Bernal, M. Aragón, Y. Baena, Dry powder formulation from fruits of Physalis peruviana L. standardized extract with hypoglycemic activity. Powder Technol. **301**, 839–847 (Aug. 2016). https://doi.org/10.1016/j.powtec.2016.07.008
142. R.C. Pereira, A.D.R. Pontinha, M. Pineiro, J.S. de Melo, A comprehensive spectral, photophysical and electrochemical study of synthetic water-soluble acridones. A new class of pH and polarity sensitive fluorescent probes, Dyes and Pigments, vol. 166, pp. 203–210, Aug. 2019, https://doi.org/10.1016/j.dyepig.2019.03.028
143. L. Acosta-Vega, J.F. Martínez-Suárez, F.S. Sánchez-Garzón, M. Hernández-Carrión, L.S. Nerio, Optimization of the encapsulation process of Cupuassu (Theobroma grandiflorum) pulp by spray drying as an alternative for the valorization of amazonian fruits. LWT. **184**, 114994 (Aug. 2023). https://doi.org/10.1016/j.lwt.2023.114994
144. Z.T. Marín-Arango, M. Cortés R, and, L.M. Agudelo-Laverde, Effect of storage on the quality of Andean blackberry (Rubus glaucus Benth) powder biofortified with Lacticaseibacillus casei ATCC393, Food Packag Shelf Life, vol. 40, p. 101180, Aug. 2023, https://doi.org/10.1016/j.fpsl.2023.101180
145. L.S. Chang, R. Karim, S.M. Abdulkarim, Y.A. Yusof, H.M. Ghazali, Storage stability, color kinetics and morphology of spray-dried soursop (Annona muricata L.) powder: effect of anticaking agents, Int J Food Prop, vol. 21, pp. 1937–1954, Aug. 2018, https://doi.org/10.1080/10942912.2018.1510836

146. B. Adhikari, T. Howes, B.J. Wood, B.R. Bhandari, The effect of low molecular weight surfactants and proteins on surface stickiness of sucrose during powder formation through spray drying, J Food Eng, vol. 94, pp. 135–143, Aug. 2009, https://doi.org/10.1016/j.jfoodeng.2009.01.022
147. D. Arslan, M.M. Özcan, Evaluation of drying methods with respect to Drying Kinetics, Mineral Content, and Color characteristics of savory leaves. Food Bioproc Tech. **5**, 983–991 (Aug. 2011). https://doi.org/10.1007/s11947-010-0498-y
148. F. Clydesdale, Mineral additives, *Nutrient Addition to Food. Nutritional, Technological and Regulatory Aspects*., Food and Nutrition Press Inc, 1999
149. R. Chang, *Principios Esenciales De Química General*, 4th edn. (Mc Graw Hill Interamericana, 2006)
150. A.G. Hall, J.C. King, Zinc fortification: current Trends and Strategies. Nutrients. **14**, 3895 (Aug. 2022). https://doi.org/10.3390/nu14193895
151. L. Frommherz, Y. Martiniak, T. Heuer, A. Roth, S.E. Kulling, I. Hoffmann, Degradation of folic acid in fortified vitamin juices during long term storage. Food Chem. **159**, 122–127 (2014). https://doi.org/10.1016/j.foodchem.2014.02.156