



RESEARCH ARTICLE

Biofortified andean blackberry (*rubus glaucus* benth) powder with *Lacticaseibacillus casei*: process and formulation effects

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Abstract

Background: Physical, chemical, bromatological and morphological characteristics are some of the quality aspects that regulate food products. The Andean blackberry is a very perishable fruit, due to its moisture, acidity, and water activity. Dehydration is one of the most common techniques in food preservation.

Methods: In this research, blackberry concentrate, inulin and *Lacticaseibacillus casei* (*L. casei*), were co-encapsulated by spray drying using different conditions: maltodextrin (MD: 4-8%), inlet air temperature (IAT: 120-140 °C), outlet air temperature (OAT: 70-80 °C) and atomizing disc speed (ADS: 20000-24000 rpm).

Results: The experimental optimization had a desirability function (71.9%), MD (5.0%), IAT (121.1 °C), OAT (71.6 °C) and ADS (24000 rpm). Physicochemical characteristics and antioxidant capacity were determined in spray dried product. The blackberry powder biofortified with *L. casei* and inulin (BPLI) achieved 7.12±0.69 Log CFU/g, total phenols (2912.9±96.4 mg eq-gallic acid/100g), anthocyanins (202.9±5.2 mg eq-cyd-3-glu/100g), and antioxidant capacity (ABTS: 2423.1±96.6 mg Trolox/100g and DPPH: 3302.6±76.4 mg Trolox/100g).

Conclusions: The physicochemical properties of biofortified blackberry powder indicate that it is a product with appropriate solubility, humidity, and water activity for consumption and storage. BPLI has the potential to be a health food and could be positioned as a functional food due to its probiotic and prebiotic characteristics and the antioxidants that are beneficial to modern consumers; on the other hand, it represents a raw material with potential use in the food industry.

Keywords

Rubus glaucus Benth, probiotics, prebiotics, antioxidants, microencapsulation, physico-chemical properties



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Abbreviations

SD: Spray Drying
 CFU: Colony forming units
 BPLI: Blackberry powder biofortified with *Lacticaseibacillus casei* and inulin
 MD: Maltodextrin
 IAT: Inlet Air Temperature
 OAT: Outlet Air Temperature
 ADS: Atomizer disc speed
 M: Moisture
 a_w : Water activity
 TP: Total phenols
 S: Solubility
 H: Hygroscopicity
 L*: Lightness
 a*: Chromaticity red/green
 b*: Chromaticity yellow/blue
 D₁₀: Percentile 10%
 D₅₀: Percentile 50%
 D₉₀: Percentile 90%
 Y: Yield
 GAE: Galic acid equivalent
 DPPH: 2,2-diphenyl -1-picrylhydrazyl radical
 ABTS⁺: 2,2'-azinobis- (3-ethylbenzothiazoline-6-sulphonate) radical cation

Introduction

The Andean blackberry (*Rubus glaucus* Benth) is a native fruit of the high tropical Andean region of the Americas. This fruit belongs to the Rosaceae family (Schulz & Chim, 2019) and contains a diversity of active components as phenolic compounds, which include anthocyanins (mainly cyanidine-3-glucoside, and procyanidins) ellagitannins and flavonols (Yang *et al.*, 2022; Schulz & Chim, 2019; Fernandes *et al.*, 2018). Furthermore, blackberries have a significant content of vitamins (A, C, E, K, and B), and minerals (Ca, P, K, Mg, Fe) (Schulz & Chim, 2019; Oszmiański *et al.*, 2015). This composition imparts relevant functional characteristics to blackberries, such as: reducing blood pressure, protecting against hepatic lesions, acting as an anti-inflammatory, being antimicrobial, and suppressing human cancer cells (Schulz & Chim, 2019).

Nowadays, consumers demand stable and functional foods that are easy to prepare and provide nutritional value that generate health benefits (Liu *et al.*, 2022). Fresh fruits offer important antioxidant compounds, which, under appropriate processing conditions, can be turned into powders that meet current market demands. The incorporation of probiotics and prebiotics in formulations can further enhance their functional properties (Guergoletto *et al.*, 2017; Huang *et al.*, 2017).

According to the International Scientific Association for Probiotics and Prebiotics (ISAPP), probiotics are “live microorganisms that, when administered in adequate amounts, confer a health benefit on the host” (Hill *et al.*, 2014). They also have a positive impact on aspects such as maintaining intestinal microbiota, improving the immune system, and reducing blood pressure, among others (Das *et al.*, 2022). Some studies have evaluated the probiotic encapsulation in fruit-based matrices using spray drying (SD): *Lactobacillus rhamnosus* in orange juice (Sengun *et al.*, 2020), *Bifidobacterium* spp. in jussara juice (Paim *et al.*, 2016), *Lactobacillus casei* in orange, pineapple, and raspberry juices (Olivares *et al.*, 2019), *Lactobacillus plantarum* ATCC 14917 in fermented pomegranate juice (Mantzourani *et al.*, 2019), and *Lactobacillus casei* LPAA 02 in acerola-siriguela juice (Souza *et al.*, 2021), inter alia.

On the other hand, the ISAPP definition of prebiotics is “a substrate that is selectively utilized by host microorganisms conferring a health benefit” (Gibson *et al.*, 2017). Inulin is considered a prebiotic fibre because it is a non-digestible oligosaccharide which is recognized as a safe food that has a positive impact on health (Carlson *et al.*, 2018). Other research suggests that inulin promotes the growth of bifidobacteria and lactobacilli (Oluwatoyin *et al.*, 2022; Luca & Oroian, 2019). Additionally, prebiotics have been shown to reduce blood pressure, glucose, cholesterol, triglycerides, and phospholipids in blood (Tawfick *et al.*, 2022). Some authors report that adding inulin could improve cell survival during spray drying. Kingwatee *et al.*, (2015) studied lychee juice with added *Lactobacillus casei* 01 and different mixtures of encapsulants and inulin, and identified that when inulin was added cell survival increased to 1 or 2 Log CFU/g.

Spray drying (SD) is a widely used encapsulation technology in both the food and pharmaceutical industry, which allows the active compounds, including: vitamins, phenols, anthocyanins, (Jafari, *et al.*, 2023; Araujo-Díaz, *et al.*, 2017), probiotic microorganisms, prebiotics (Wang *et al.*, 2022) and colorants, to be encapsulated. One of the main advantages of this technology is the short residence time, making it ideal for heat sensitive products and resulting in successful retention of flavour, colour, and nutrients.

The quality of the powdered product obtained by SD depends on the physicochemical stability of the feed, which is typically a colloidal system such as an emulsion, suspension, or mixture where different forces are involved: Van der Waals, electrostatic, steric, hydration, hydrophobic and phase separation (Mateos & Palazzo, 2022). Likewise, feeding properties (total solids, viscosity, density, surface tension, particle sizes, zeta potential, and spectral absorption index) play an important role on their stability (Tontul & Topuz, 2017; Marulanda *et al.*, 2018). In the same way, the type of encapsulant used affects the powder quality (Lee *et al.*, 2018), as well as the design characteristics of the equipment (atomizing disc, number, height and length, nozzle or pressure nozzle, size and number, two fluid nozzles, type of flow co-current/counter-current/mixed) (Tontul & Topuz, 2017) and operating conditions (air inlet temperature, air outlet temperature/feed flow, drying air flow/residence time/pressure of the drying chamber, atomizing disc speed/pressure at the nozzle or nozzles) (Shishir & Chen, 2017).

The blackberry has high potential in the food industry due to its nutritional and sensory qualities, but its perishable nature with high respiration rates and a short post-harvest life limit its fresh marketing (Horvitz *et al.*, 2017). Spray drying offers an effective alternative to preserve and improve fruit characteristics by converting a fruit suspension into a stable powder with longer shelf life (Tontul & Topuz, 2017). In this context, the aim of this research was to assess the impact of formulation and the spray-drying process on blackberry powder and its effect on physicochemical properties, the viability of the microorganism *Lactocaseibacillus casei*, and the antioxidant capacity of the product.

Methods

Materials

The materials used were Andean blackberry concentrate (Nutrium S.A.S, Medellín, Colombia, 13-15 °Brix, citric acid 3.1-5.5%, and pH 2.5-3.5), maltodextrin DE 18-20 (Ingredion Colombia S.A; Medellín, Colombia), inulin (Fibruline S20, Cosucra, Warcoing, Belgium), probiotic microorganism *L. casei* ATCC 393 (Microbiologics, St. Cloud, United States), broth, and agar MRS for bacteria (Man, Rogosa and Sharpe, Scharlau, Barcelona, Spain).

Obtaining biomass from *L. casei*

L. casei was activated in 10 mL of MRS broth at 37 °C for 72 h in anaerobiosis. Then, 90 mL of broth was added, and it was incubated at 37 °C for between 8-9 h (exponential phase). Later, it was added to 900 mL of culture medium and incubated for between 14-15 h (early stationary phase) at the same temperature. Finally, it was centrifuged at 440 g for 15 min at 25 °C, the supernatant was removed, and the biomass was obtained by washing the pellet with sterile water.

Preparation of the blackberry suspension with probiotics and prebiotics

Batches of 2000 g were prepared; initially the blackberry concentrate was dissolved until a suspension with a solid content of 8.8% was obtained by using a Silverson L5M-A (Chesham, United Kingdom) homogenizer for 10 min at 10000 rpm. Also, a premix of maltodextrin (MD), inulin (3.06% w/w) and water (homogenized for 5 min at 10000 rpm) was prepared; the biomass was then added ($\approx 8.58 \times 10^{10}$ CFU/g) to this and the process continued at 2000 rpm for 1 min. This last premix was then incorporated into the blackberry suspension manually, and finally it was homogenized at 10000 rpm for 1 min.

Spray drying process

A pilot SD equipment (Vibrasec PASALAB, Medellín, Colombia), 1.5 co-current flow operated at subatmospheric pressure (0.373 kPa) was used. The response surface methodology was used with a face-centered ($\alpha=1$) central composite experimental design with 21 experiments (Table 1). The independent variables are the following: MD (4-8%), air inlet temperature (IAT) (120-140°C), air outlet temperature (OAT) (70-80°C), and atomizing disc speed (ADS) (20000-24000 rpm). The dependent variables are the following: viability *L. casei* (LogCFU/g), moisture (M), water activity (a_w), total phenols (TP), antioxidant activity (DPPH, ABTS), anthocyanins, solubility (S), hygroscopicity (H), colour (L*: luminosity, a*: red/green chromaticity and b*: yellow/blue chromaticity), particle size (D_{10} , D_{50} , D_{90}), and finally the process yield (Y). In order to minimize the effect of the temperature in the drying chamber, the dust was removed every 15 minutes. The dust collected in the jacketed cyclone container was cooled using water at 30 °C in order to favour the survival of the microorganism.

Table 1. Experiment design of the spray drying process.

Randomization	Experiments	IAT (°C)	OAT (°C)	ADS (rpm)	MD (%)
1	1	140	80	24000	4
14	2	130	75	24000	6
17	3	130	75	22000	6
8	4	120	70	20000	4
3	5	140	70	24000	8
4	6	120	80	20000	8
11	7	130	70	22000	6
13	8	130	75	20000	6
18	9	130	75	22000	6
2	10	140	80	20000	4
6	11	120	70	24000	4
15	12	130	75	22000	4
7	13	120	80	24000	8
9	14	120	75	22000	6
20	15	130	75	22000	6
12	16	130	80	22000	6
5	17	140	70	20000	8
16	18	130	75	22000	8
21	19	130	75	22000	6
10	20	140	75	22000	6
19	21	130	75	22000	6

To determine the optimal operating conditions, an experimental optimization process was conducted. A criterion was established for each dependent variable to achieve the best quality attributes in the BPLI powder. The dependent variables were modelled using a second-order polynomial equation (Equation 1). Model fit was evaluated using the lack of fit method and the regression coefficient (R^2). The experimental values at the optimum conditions were obtained from three replicates and compared to the theoretical value of the mathematical model to assess the accuracy of the model.

$$Y = \beta_0 + \beta_A A + \beta_B B + \beta_C C + \beta_{AB} AB + \beta_{AC} AC + \beta_{BC} BC + \beta_A^2 A^2 + \beta_B^2 B^2 + \beta_C^2 C^2 \quad (\text{Eq. 1})$$

Where Y is the dependent variable, β_0 is constant, β_A , β_B , and β_C are the linear coefficients; β_{AB} , β_{AC} , and β_{BC} are the coefficients of the interaction of the linear factors; and β_A^2 , β_B^2 , and β_C^2 are the quadratic coefficients.

Count of *Lactocaseibacillus casei*

10 g of suspension were homogenized with 90 mL of universal peptone (0.1% w/v), and successive dilutions up to 10^9 were made. These dilutions were prepared in order to attain greater accuracy in colony number counting (Marín-Arango *et al.*, 2019). For the blackberry powder, 10 g was rehydrated in 90 mL of saline solution (0.85% w/v); this was stored for 30 min at room temperature to activate the microorganism, and then serial dilutions up to 10^6 were prepared. The samples were inoculated into the MRS agar by the deep inoculation method, and the cultures were incubated at 37 °C for 72 h for the suspension, and 240 h for the blackberry powder under anaerobic conditions.

The *L. casei* survival rate was determined according to dos Santos *et al.* (2019), employing Equation 2:

$$\% \text{Survival} = \left(\frac{N}{N_0} \right) \times 100 \quad (\text{Eq. 2})$$

Where N is Log CFU/g after spray drying process, and N_0 is Log CFU/g of feed suspension.

Characterization of BPLI properties

Physicochemical characteristics

Moisture (M) and water activity (a_w)

The M was determined with a vacuum furnace at 60 °C to constant weight (AOAC, 2012), and the a_w was determined with a dew point hygrometer Aqualab 4TE (Decagon Devices, Pullman, United States) at 25 °C (AOAC, 2012).

Solubility (S)

The S was carried out following Cano-Chauca *et al.*'s (2005) method with modifications: 100 mL of distilled water was homogenized with 1 g of blackberry powder for 3 min, the suspension was transferred to falcon tubes, and then centrifuged at 1060 g for 15 min. Subsequently, a 25 mL aliquot of the supernatant was taken in a Petri dish and placed in the oven at 110 °C for 1 h; thus, the weight of dry solids was obtained ($W_{SS-25mL}$). S was calculated according to Equation 3, expressed in % dry base (db).

$$S = \frac{W_{SS-25mL} * 4}{W - \left(\frac{M(\%)}{100}\right)} * 100 (\%db) \quad (\text{Eq. 3})$$

Where, $W_{SS-25mL}$ is weight of dry solids, W is sample weight, and M is moisture percentage.

Hygroscopicity (H)

The powder's hygroscopicity was determined according to the methodology described by Martínez-Navarrete *et al.* (1998). Approximately 2 g of the powder sample was added to a glass vessel and placed inside an airtight flask containing another vessel with a saturated potassium iodide (KI) solution (a_w KI 25 °C = 0.689). The bottle was placed in a Memmert ICH-256-L chamber (Schwabach, Germany) at 25 °C, relative humidity (RH) 65% for 4 weeks, and the equilibrium humidity was determined at the end of this period.

Colour

The colour was determined according to Ferrari *et al.*'s (2012a) methodology using an X-Rite sphere spectrophotometer, model SP64 (Grand Rapids, United States), illuminant D65, observer 10°, and the specular component excluded. Colour on the surface of the samples was reported in the CIELAB colour space, where L^* is luminosity, a^* and b^* are chromaticity parameters.

Particle size

The particle size was determined using the Mastersizer 3000 (Malvern Instrument Ltd, Malvern, United Kingdom) by laser diffraction, AERO S cell, and the MIE dispersion model with an absorption index of 0.5 and a refractive index of 1.45; particle size was expressed in percentiles (D_{10} , D_{50} , D_{90}).

Yield

The Y of the product was determined as the ratio of the kg solids in the powder obtained and the kg solids in the SD feed (Tontul & Topuz, 2017).

Total phenols, anthocyanins, and antioxidant capacity

Extraction to determine TP and antioxidant activity was performed according to the Fang & Bhandari (2011) modified methodology. 0.1 g of blackberry powder was mixed with 40 mL of a methanol/water solution (70:30); the resulting mixture was centrifuged at 7080 g for 15 min at 20 °C and then passed through the qualitative filter paper (Boeco, pore between 8-12 µm). The supernatant was gauged at 50 mL with methanol/water.

Total phenols

The Folin-Ciocalteu colorimetric method was used for the quantification of TP, following the method described by Zahoor *et al.* (2018) with some modifications: 100 µL of the extract was mixed with 400 µL of sodium carbonate solution (Na₂CO₃) 0.07 M, shaken in a vortex, and left to stand for 5 min. Then 500 µL of the folin reagent (Merck, Rahway, United States) was diluted in distilled water (1:10 mL was added in a volumetric flask). After a 2 h reaction, absorbance was measured at 760 nm in a UV-vis spectrophotometer (Thermo Fisher, Waltham, United States). The results were expressed as mg eq gallic acid (GAE)/100g on a wet basis.

DPPH and ABTS

The antioxidant activity was determined according to Thaipong *et al.*'s (2006) methodology, using two reactions: DPPH radical (2,2-diphenyl-1-picrylhydrazyl, Merck, Rahway, United States) at 517 nm and ABTS⁺ [2,2'-azinobis- (3-ethyl-benzothiazoline-6-sulphonate)], Merck, Rahway, United States) at 734 nm. 950 µL of a dissolution of each radical, and 50 µL of the extract were added and stored in the absence of light (30 min for DPPH) and (7 min for ABTS). Results were expressed as mg eq-Trolox/100g wet basis (mg eq-Trolox/100g).

Anthocyanins

Anthocyanins extracts were obtained following the methodology described by Awika *et al.* (2005) with modifications. 0.5 g BPLI was extracted using 10 mL of acidified methanol (1% v/v HCL) in an ultrasonic bath for 20 min. The mixture obtained was centrifuged at 7000 g for 10 min, then the supernatant was decanted, and the residue was extracted consecutively with the solvent (2 x 7.5 mL). The supernatants were diluted in a 25 mL volumetric flask. The anthocyanin content was determined by the differential pH spectrophotometric method (AOAC, 2012) and expressed as cyanidine-3-glucoside (cyd- 3-glu). 2 mL of the sample were diluted to 10 mL with potassium chloride (0.025 M), and sodium acetate (0.4 M), which were used as buffer solutions at a pH of 1.0 and 4.5, respectively. To determine the anthocyanin content of BPLI, Santos *et al.*'s (2019) methodology was followed with modifications using Equations 4 and 5.

$$A = (A_{520} - A_{700})_{pH\ 1.0} - (A_{520} - A_{720})_{pH\ 4.5} \quad (\text{Eq. 4})$$

$$mg\ cyd - 3 - glu / 100g\ wb = \frac{A * MW * DF * 10^3}{\epsilon} * \frac{v}{10^3} * 100 \quad (\text{Eq. 5})$$

Where A₅₂₀ and A₇₀₀ (absorbances of each solution at 520 nm and 700 nm), MW (molecular weight of cyd-3-glu) = 449.2 g/mol, DF = dilution factor, ε (molar extinction coefficient for cyd-3-glu) = 26900 L mol⁻¹ cm⁻¹ and 10³ = conversion factor from g to mg and from mL to L, W = sample weight (g), and v = dilution volume (mL).

Data analysis

The results were analysed using Statgraphics Centurion® XVII.II (Statpoint Technologies, Inc.) software, and the analysis of variance (ANOVA) was performed with a 5% significance level and multiple response optimization. R studio can also be used for data analysis.

Results and Discussion

Figure 1 displays the response volume graph of *L. casei* viability (Figure 1a), total phenol content (Figure 1b), antioxidant capacity (Figures 1c and 1d), anthocyanins content (Figure 1e), powder hygroscopicity (Figure 1f), solubility (Figure 1g) and colour parameters (Figure 1h and 1i) in biofortified blackberry powder. The above-mentioned characteristics show significant statistical differences (p < 0.05). In the same way, Table 2 shows the ANOVA (p-values) of the dependent variables with respect to the independent variables and their linear and quadratic interactions, where it was observed that variables M, a_w, DPPH, b*, D₁₀, D₅₀, D₉₀, and Y did not have significant differences (p < 0.05).

Viable cell count *L. casei* ATCC 393

The viability of the microorganism was evaluated through cell counts and reported as log CFU/g. The suspension containing blackberry concentrate, probiotic, and inulin showed an average microbial count of 10.4 ± 0.6 Log CFU/g. After SD, a lethal effect was observed, where the count fluctuated between 6.1 and 7.9 Log CFU/g, corresponding to a survival rate of 58.6 and 76.0%, respectively. These results adhered to both Colombian and international regulations (> 10⁶ CFU/g) (Minsalud, 2011; Liao *et al.*, 2017). The microorganism survival rate in the BPLI was affected by SD, with a decrease of 2 logarithmic units. Dos Santos *et al.* (2019) reported that in free cells of *Lactobacillus acidophilus* La-5 microencapsulated with inulin by spray drying, there was a reduction between 3.8 and 1.5 Log CFU/g, equivalent to a survival rate in the range of 62.2 and 86.5%.

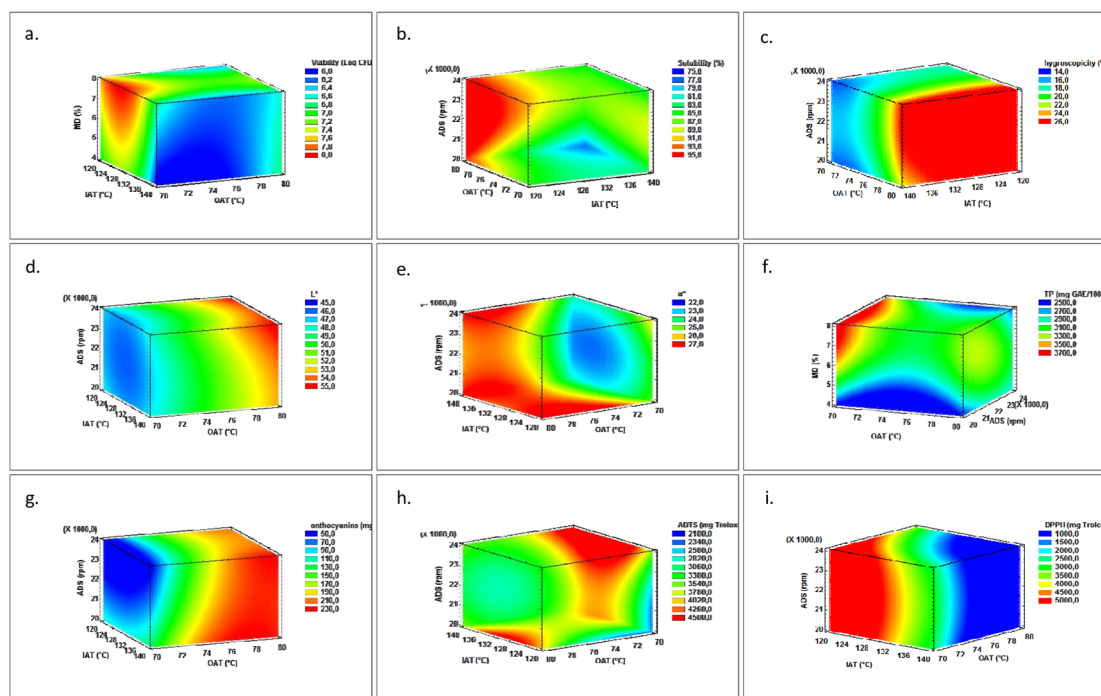


Figure 1. Response volume graphs of BPLI, obtained by SD. 1a. *L. casei* viability, 1b. Solubility, 1c. Hygroscopicity, 1d. Luminosity (L^*), 1e. Chromatic variable a^* , 1f. Total phenol (TP), 1g. Anthocyanins, 1h. ABTS $^+$, 1i. DPPH.

The response volume graph (Figure 1a) shows a higher viability of *L. casei* when SD operates at low IATs and OATs (120 and 70 °C) when the MD proportion varies between 6 and 8%. No significant differences were observed in relation to the ADS range (20000-24000 rpm), (Table 2). This behaviour could be attributed to the action of MD and inulin as thermoprotective agents and the growth stimulants of *L. casei*, which minimize different types of stress associated with loss of viability: oxidative, osmotic and mechanical, and desiccation (Kalita *et al.*, 2018, Huang *et al.*, 2017). However, thermal stress caused by high IAT and OAT in SD has been reported as one of the main factors influencing the survival of the microorganism (Huang *et al.*, 2017; Zhang *et al.*, 2016). Since it modifies the cell wall, there is a possible loss of the integrity of the lipid bilayer and the deterioration of cell membrane functions, which could contribute to breaking DNA chains (Perdana *et al.*, 2013).

Another critical factor is the early stationary phase in which the microorganism was inoculated, which allows greater viability during drying because physiological states are induced that trigger survival response to stress (Huang *et al.*, 2017).

L. casei type microorganisms exhibit different responses in survival levels in SD processes depending on probiotic, wall material, food matrix, and process condition employed: 81% with *L. casei*, *L. rhamnosus*, and *L. plantarum* in acerola-siriguela juice with 5% MD (IAT: 140 °C) (Souza *et al.*, 2021); 72.5% with *L. casei* ATCC 393 in skimmed milk (IAT: 170 °C, OAT: 80/85 °C) (Dimitrellou *et al.*, 2016); 40% with *L. casei* BL 23 in sweet whey (IAT: 170 °C and OAT: 63 °C) (Huang *et al.*, 2016); 70% with *L. casei* NRRL B-442 in cashew apple juice (IAT: 120 °C and OAT: 75 °C, encapsulant MD and MD+gum arabic (GA)) (Pereira *et al.*, 2014); 52.4% with *L. casei* in orange powder (IAT: 140 °C, OAT: 85-95 °C, MD encapsulant) (Alves *et al.*, 2016); and finally, 5.7 and 6.8 Log CFU *L. casei*/mL in lychee powder (IAT: 150-170 °C and OAT: 60-90 °C, MD encapsulants, inulin, GA) (Kingwatee *et al.*, 2015).

To identify the prebiotic characteristic of BPLI, the content of MD and inulin present in 26.12 g of the powder (10% solids) reconstituted in 250 mL of water was theoretically calculated. In this portion, 7.65 g of MD and 4.73 g of inulin were obtained. According to ISAPP (Gibson *et al.*, 2017) the amount required to designate a product as a prebiotic is 3 g per day; therefore, in this case, the BPLI could be considered as a powder with prebiotic characteristics.

Moisture and water activity (a_w)

The mean values of M and a_w of BPLI ranged between 2.1-5.6% and 0.202-0.317, respectively; no significant differences were observed (Table 2). Similar results were obtained by Souza *et al.* (2021) in juice powders with probiotics. In the

Table 2. ANOVA of the spray drying process to obtain BPLI.

Source	p-value															
	Viability	M	a _w	TP	ABTS	DPPH	Anthocyanins	S	H	L*	a*	b*	D ₁₀	D ₅₀	D ₉₀	Y
A: IAT (°C)	0.5594	0.2801	0.1324	0.2437	0.2569	0.4124	0.6923	0.2279	0.2119	0.9125	0.1145	0.9503	0.1042	0.3118	0.9566	0.0794
B: OAT (°C)	0.7416	0.3205	0.3842	0.2905	0.9410	0.0788	0.0424*	0.3811	0.0298*	0.0289*	0.0056*	0.1943	0.3501	0.3542	0.2414	0.5512
C: ADS (rpm)	0.6637	0.5670	0.8952	0.8636	0.0216*	0.9826	0.2149	0.5177	0.6639	0.4545	0.2932	0.2806	0.0703	0.0819	0.8212	0.9271
D: MD (%)	0.7246	0.5077	0.2064	0.1517	0.1208	0.9079	0.4477	0.4934	0.8894	0.5768	0.4140	0.5640	0.9140	0.7735	0.9509	0.0581
AA	0.0462*	0.1194	0.9208	0.4424	0.0025*	0.5558	0.5530	0.3547	0.4762	0.3628	0.0471*	0.6746	0.1127	0.1412	0.3157	0.5087
AB	0.4548	0.2924	0.2209	0.1795	0.0820	0.9150	0.9994	0.2335	0.9430	0.9426	0.5564	0.2170	0.8097	0.9528	0.9899	0.4436
AC	0.7950	0.3589	0.3761	0.1652	0.8967	0.9429	0.9971	0.2976	0.2789	0.7333	0.3397	0.6709	0.2144	0.1678	0.5304	0.8974
AD	0.9815	0.6362	0.3951	0.3431	0.2532	0.1345	0.1223	0.9662	0.0509	0.0667	0.0117*	0.2305	0.3836	0.3297	0.2982	0.6346
BB	0.2719	0.5696	0.8016	0.0300*	0.0209*	0.5315	0.1185	0.9960	0.0990	0.8488	0.0043*	0.2505	0.1393	0.3958	0.5474	0.3164
BC	0.9995	0.3173	0.3682	0.4447	0.0269*	0.9591	0.1897	0.2151	0.3365	0.5408	0.7131	0.6457	0.9426	0.9329	0.9743	0.7568
BD	0.5975	0.2270	0.1687	0.4677	0.0249*	0.7875	0.9965	0.1360	0.1266	0.6733	0.5798	0.9362	0.3758	0.6885	0.8454	0.0943
CC	0.1983	0.5399	0.7594	0.2519	0.0508	0.6806	0.8030	0.0457*	0.4219	0.6248	0.0390*	0.4279	0.7521	0.5010	0.2390	0.9028
CD	0.1223	0.3771	0.9478	0.0473*	0.2590	0.9889	0.4775	0.0853	0.1562	0.9833	0.4079	0.9727	0.3844	0.5928	0.9165	0.5077
DD	0.9656	0.4541	0.9466	0.1281	0.2208	0.5340	0.4083	0.2649	0.1010	0.3504	0.3596	0.8557	0.6347	0.4928	0.3359	0.5068

same way, these values are within the ranges obtained by SD in blackberry-derived powders employing different encapsulants (Da Fonseca Machado *et al.*, 2018; Franceschinis *et al.*, 2014). In addition, low M and a_w values guarantee good microbiological stability (Souza *et al.*, 2021; Pereira *et al.*, 2015; Dos santos *et al.*, 2014), the long-term survival of *L. casei* in $a_w < 0.3$ matrices due to the low molecular mobility of water (Dos santos *et al.*, 2014), and, in general, have an influence on fluidity, tackiness, and stability during storage (Santhalakshmy *et al.*, 2015).

Solubility

S is a property of great interest in the powder industry and is much appreciated by the modern consumer. It depends on multiple factors such as those proper to the composition of the raw material, the surface area of particles, and the type of encapsulant used (Tontul & Topuz, 2017). Figure 1b shows the response surface plot for the S of BPLI. There were significant differences in the quadratic interaction of the ADS for solubility ($p < 0.05$) as shown in Table 2, which is represented by the curvature and maximizes S at 22000 rpm. Mean values between 76.9 ± 2.3 – $94.8 \pm 1.3\%$ were observed in biofortified blackberry powder. In general, the BPLI presented a good S attributed to the affinity of its components with the aqueous phase, which allows easy diffusion of the water through the interior of its structure which is enhanced by the MD. The S of the biofortified powder is enhanced when the system operates under conditions of IAT (120–128 °C), and OAT (72–80 °C), in the whole range of ADS and MD. The lowest S values were found when the ADS was 20000 rpm, IAT: 136–140 °C, and OAT: 76–80 °C. This last behaviour is contrary to what was reported by some authors who associate the increase of the S with the increase of the IAT (Tontul & Topuz, 2017) when MD and OAT are high.

Some researchers have reported S values in several food matrices: Ávila *et al.* (2015) reports high values in sugar cane (97.87–98.1%) due to high sugar content and hydroxyl (OH) groups in molecules. On the other hand, Gagneten *et al.* (2019) reported S values of 95.4, 92.5, and 93.2% in raspberry powder, blackcurrant, and elderberry respectively. Franceschinis *et al.* (2014) reported values of S in blackberry powder with MD and MD-Trehalose (98.63–100%) that had a MD of 40%.

Hygroscopicity

H is a physical property that reflects the level of a material of water adsorption in a known RH medium. In powdered food products, lower H values help to avoid stickiness problems (Tontul & Topuz, 2017). Figure 1c presents a hygroscopicity response surface plot. The mean H values for BPLI varied between 14.5 ± 0.5 – $24.4 \pm 0.2\%$ and showed significant differences ($p < 0.05$) with respect to OAT. These values were higher as the OAT increased. This behaviour was consistent with the lower values of a_w and humidity in the BPLI at a high OAT, which increases the adsorption force and the motive force to the transfer of water mass from the controlled environment to the food. Similar values have been reported in blackberry powder obtained by SD (18.8–27.3 g/100 g bs) (Ferrari *et al.*, 2012a); while Gagneten *et al.* (2019) reported $H < 20\%$ in raspberry powder, blackcurrant, and elderberry (13.1 ± 0.9 ; 11.8 ± 0.3 , and $12.7 \pm 1.5\%$ respectively) using MD 20% as an encapsulant. The least hygroscopic BPLI was obtained at high IAT (140 °C) and low OAT (70–74 °C), MD (4–6%), highlighting that the MD had a contrary effect to what Tontul & Topuz, (2017) reported. It could possibly form a complex MD, inulin, and sugars with lower adsorption strength.

Colour

The BPLI colour is one of the most attractive features of the product. It is described as having the classic pink colour, attributed to the anthocyanins content and the air occupied in the interior space of its structure, which generates greater homogeneity of the refraction index that makes the product clear (Cortés-Rodríguez, 2004). This is intensified by the presence of the MD due to the dilution effect. The L^* and a^* showed significant differences ($p < 0.05$) with respect to OAT (Figure 1d and 1e, respectively). Additionally, a^* exhibited these differences regarding the linear interaction IAT-MD and the IAT, OAT, and ADS quadratic interactions. However, it stands out that despite the statistical variations (Table 2), the colour of the BPLI was not a critical variable since the changes found were small (L^* : 46.0–52.8, a^* : 22.5–27.2 and b^* : 3.0–4.5) and unnoticeable to the human eye. Several authors reported this situation (avocado powder: Marulanda *et al.*, 2018; coconut powder added with active components during storage: Lucas-Aguirre *et al.*, 2019). The BPLI colour parameters are located in the I quadrant of the a^*b^* chromatic plane, in the grey zone that gives it a matte appearance, a predominance of reddish pigmentation tones, and low intensity of yellow tones. Some research on blackberry powder colour with MD and MD-Trehalose has reported higher L^* and b^* values in products obtained by SD rather than lyophilization; however, chromaticity a^* was not affected (Franceschinis *et al.*, 2014). On the other hand, Ferrari *et al.* (2012a) reported an increase in L^* (clearer) with the increase in MD.

Particle size

The D_{10} , D_{50} , and D_{90} percentiles did not differ significantly from the independent variables (Table 2); their mean values fluctuated as did their standard deviation for D_{10} (10.0 ± 0.2 – $18.8 \pm 0.2 \mu\text{m}$), D_{50} (24.2 ± 0.3 – $34.0 \pm 0.4 \mu\text{m}$), and D_{90} (44.1 ± 0.9 – $254 \pm 9.7 \mu\text{m}$). In general, low particle sizes were observed, which increases the surface area of the particles

and favours a greater degradation of sensitive compounds (Tontul & Topuz, 2017). Some authors have reported particle size values in berries: Gagneten *et al.* (2019) for raspberry powder [D_{10} ($4.22 \pm 0.19 \mu\text{m}$), D_{50} ($7.48 \pm 0.26 \mu\text{m}$), and D_{90} ($13.41 \pm 0.49 \mu\text{m}$)] and for blackcurrant [D_{10} ($4.64 \pm 0.15 \mu\text{m}$), D_{50} ($8.3 \pm 0.0 \mu\text{m}$) and D_{90} ($14.4 \pm 0.4 \mu\text{m}$)]. Some differences were observed between the results of this study and those reported in previous research, which may be due to factors such as the type of fruit, processing, and spray drying conditions that impact the final particle size.

Yield

Y had values between 47.7 to 73.4%, which could be attributed to the loss of solids that adhered to the walls of the interior drying chamber due to the adhesiveness of the particles with the metallic material and the cohesiveness between the same particles. Other causes not associated with the SD process must also be considered such as the loss of solids due to the material that adhered to the walls of the feed preparation tank and the pipes that adhered to the atomizing disc. The total sum of these losses represents a high percentage value due to the fact that the batches for each experiment were 2 kg. A tendency to improve the Y with an increase in MD is highlighted, which could be attributable to a synergistic effect with the prebiotic fibre. Furthermore, to improve the yield process, one potential solution could be to dry larger batches exceeding 2 kg, or to implement a continuous feeding system for the suspension. Some authors have reported a similar situation in cactus pear powder with MD and inulin (Saenz *et al.*, 2009) and in powder of sugar cane with MD (Ávila *et al.*, 2015). Other authors have reported a higher yield of jussara powder with starch than in a mixture of inulin and MD (Paim *et al.*, 2016); however, the authors conclude that the latter are essential for the conservation of anthocyanins.

Total phenols, anthocyanins, and antioxidant capacity

Figure 1 shows the results obtained for TP, anthocyanins and antioxidant capacity determined by DPPH, and ABTS⁺ in BLPI, where an effect due to the independent variables associated with the SD process was observed: TP (3699.1 ± 15.1 - 2467.5 ± 87.9 mg GAE/100g), anthocyanins (228.6 ± 5.0 and 52.6 ± 6.3 mg eq-cyd-3-glu/100g), and the antioxidant capacity ABTS (2165.3 ± 27.1 - 4463.7 ± 120.0 mg eq-Trolox/100g) and DPPH (1011.7 ± 21.6 - 5519.9 ± 14.9 mg eq-Trolox/100g); all of these values are lower compared to those of the blackberry concentrate and the suspension (Table 3).

TP were statistically affected by linear ADS-MD interaction and quadratic OAT interaction (Table 2). The most favourable operating conditions were low OAT (70 °C), MD between 6 and 8%, ADS in the range 20000-24000 rpm

Table 3. Results of the experimental optimization of the BPLI.

Response	Criteria	Weight	Impact	Predicted value	Experimental Value	Residual error
Viability (CFU/g)	Maximized	2.0	5	7.5	7.12 ± 0.69	4.4
M (%)	Mean value	0.5	3	3.9	4.29 ± 0.25	10.8
a_w	Mean value	0.5	3	0.260	0.191 ± 0.011	26.5
TP (mg GAE/100 g)	Maximized	1.0	4	3367.4	2912.8 ± 96.4	13.5
ABTS (mg eq-Trolox/100g)	Maximized	1.0	4	3699.2	2423.1 ± 96.6	34.5
DPPH (mg eq-Trolox/100g)	Maximized	1.0	4	4450.9	3302.6 ± 76.4	25.8
Anthocyanins (mg eq cyd-3-glu/100g)	Maximized	1.0	4	118.6	202.9 ± 5.2	71.1
S (%)	Maximized	0.5	3	81.6	94.2 ± 0.4	15.5
H (%)	Minimized	0.5	3	17.8	20.6 ± 0.1	15.9
L*	Minimized	0.5	3	49.1	49.5 ± 0.3	0.7
a*	Maximized	0.5	3	27.2	26.9 ± 0.2	1.0
b*	Maximized	0.5	3	4.3	4.2 ± 0.1	1.2
D_{10} (μm)	Minimized	0.5	3	13.1	15.0 ± 2.7	14.5
D_{50} (μm)	Minimized	0.5	3	26.6	30.1 ± 2.6	13.2
D_{90} (μm)	Minimized	0.5	3	116.7	129.4 ± 93.1	10.9
Y (%)	Maximized	1.0	4	66.1	73.6 ± 1.9	11.4

(Figure 1b), and IAT 120-128 °C (data not shown). This behaviour may be attributed to the lower thermal stress and the protection offered by MD-inulin on the active components. Greater values have been reported in this investigation than those in Singh *et al.* (2019) (162.6-209.9 mg GAE/100g) for Jamun powder (Indian blackberry) where the IAT > 185 °C had a significant effect; or in Franceschinis *et al.* (2014) for blackberry powder encapsulated with MD and MD+Trealosa (340±39 and 294±43 mg GAE/100g respectively). Furthermore, Colín-Cruz *et al.* (2019) reported the retention of TP in blackberry+*L. acidophilus* powder encapsulated with different wall materials: gum arabic (GA) (95.1%), MD (81.1%), whey protein concentrate (WPC) (75.7%), GA-MD (98.4%), GA-WPC (90.1%), and MD-WPC (87.1%).

Specifically, a diverse group of phenolic compounds comprising anthocyanins, monomeric phenols, and polymeric phenols have been reported for the Andean blackberry (Schulz & Chim, 2019). The cyd-3-glu and cyanidine 3-rutose are the anthocyanins most often found. Phenols are a complex group represented by flavonoids, gallic acids and derivatives, phenolic acids and derivatives, and ellagitannins. These compounds can suffer thermal damage in different ways that lead to their reduction during the SD process. The thermal deterioration of anthocyanins glucosidase is associated with the hydrolytic opening of the pyrylium ring to form chalcone glucosidase (Fernandes *et al.*, 2018). On the other hand, phenols display variability based on their chemical structure. For instance, the presence of a methoxyl group in hydroxybenzoic acids results in the loss of CO₂ and CH₃. Meanwhile, the loss of H₂O, CO₂, and C₃H₂O₂ was observed in hydroxycinnamic acid esters. Also, flavonoids and condensed tannins are labile in thermal processes; where procyanidins are the most labile phenolic compounds and are prone to generate deprotonations and multicharged ions, especially in tetramers and major oligomers (De Paeppe *et al.*, 2014).

Anthocyanins are active compounds sensitive to deterioration due to several reasons: oxygen, light, metal ions, high pH, high temperature, and residence time (Da Fonseca-Machado *et al.*, 2018). It is highlighted that the anthocyanin contents obtained fluctuated between 52.6±6.3 and 228.6±5.0 mg eq-cyd-3-glu/100g; however, these values were lower than those reported by Ferrari *et al.* (2012b) in blackberry powder obtained by SD (642.7; 628.2 and 639.0 mg/100g db), using the encapsulants MD (7%), GA (7%) and mixture MD (3.5%), and GA (3.5%), respectively. This difference could be mainly attributed to the use of blackberry concentrate in this research, which is subjected to thermal stress during the vacuum evaporation process. This could have contributed to the preliminary degradation through cyd-3-glu polymerization reactions (Wu *et al.*, 2010) that are anthocyanin predominant in blackberry pulp (Schulz & Chim, 2019; Ferrari *et al.*, 2012b).

When SD anthocyanins degrade, they show significant differences ($p < 0.05$) mainly because of the effect of the OAT factor. Unexpected behaviour was observed as there was an increasing tendency when OAT values were higher (76-80 °C). The higher anthocyanin content in BPLI is potentiated at IAT conditions (136-140 °C) and in all ADS and MD ranges. This situation could be attributed to several uncontrolled factors such as the variation of its composition in the raw material as well as to the protective effect of MD. MD is a glucose polysaccharide that can protect anthocyanins by non-covalent inclusions through hydrogen bridges and van der Waals interactions. Additionally, some authors indicate that the flavylium cation of anthocyanins with dextrans forms a complex that prevents the transformation of anthocyanins to other stability species (Colín-Cruz *et al.*, 2019). Once the anthocyanins have been included in the maltodextrin matrix, they can withstand high thermal conditions. These results are consistent with those previously obtained by other authors who indicate that dextrans adequately protect anthocyanins and phenolic compounds during spray drying processes (Colín-Cruz *et al.*, 2019; Fernandes *et al.*, 2018).

Variations of anthocyanins can also be attributed to the anthocyanin extraction method since it has been reported that they are sensitive to temperatures higher than 60 °C in acid environments. Also, there are losses between 20-50% (Araujo-Díaz *et al.*, 2017) and are considered stable below that temperature (Wang *et al.*, 2017). Da Fonseca-Machado *et al.* (2018) reported 1.36±0.08 mg eq-cyd-3-glu/g bs in anthocyanin-rich extracts of blackberry residues obtained by SD, which were in a 5:2 ratio encapsulant:extract; these indicated that high temperatures decrease the concentration of encapsulated bioactive compounds, especially when they are thermosensitive. Franceschinis *et al.* (2014) obtained the monomeric contents of anthocyanins in blackberry powder with MD and an MD-Trealosa of 70±3 and 61±2 mg of cyd-3-glu/100g, and associated losses with high process temperatures. Colín-Cruz *et al.* (2019) reported the percentage of anthocyanins retention in blackberry powder + *L. acidophilus* that were encapsulated with GA (88.4%), MD (90.4%), WPC (80.2%), GA-MD (99.0%), GA-WPC (85.9%), and MD-WPC (87.3%).

The BPLI's antioxidant activity as determined by the ABTS method did not show any defined behaviour that was statistically affected by the ADS, the linear interactions OAT-ADS and OAT-MD, and the quadratic interactions IAT and OAT for which the lower value of ABTS is shown with the reduction of the ADS. In addition, the higher values are reached with the increase of the ADS and in variable operating conditions: high OAT (78-80 °C), ADS ranging between (20000-24000 rpm); MD between 4 and 6% at low OAT (70 °C); MD between 4 and 8% at high OAT (78-80 °C); and IAT

Table 4. Regression coefficients of the spray drying process optimization.

Coefficient	Viability (CFU/g)	M (%)	a _w	TP (mg GAE/10 g)	ABTS (mg eq-Trolox/100g)	DPPH (mg eq-Trolox/100g)	Anthocyanins (mg Eq cycl-3-glu/100g)	S (%)	H (%)	L*	a*	b*	D ₁₀	D ₅₀	D ₉₀	Y (%)
constant	68.3211	352.796	-13.1522	149522	-94575.9	129084	-3274.82	-539.462	642.089	392.067	-22.5348	32.9665	296.46	296.766	5982.4	-1679.44
A: IAT (°C)	1.49784	-5.16296	0.0486365	-913.582	3094.92	-964.107	-63.6872	-2.15045	0.02086	-3.66418	-2.75524	-0.809704	3.43933	5.32646	121.325	-2.70649
B: OAT (°C)	-3.00633	-0.527065	0.213823	-3273.44	-1826.21	-3312.93	314.295	9.22142	-16.4205	0.996909	8.55377	0.936583	-12.0192	-8.16202	-179.763	49.5548
C: ADS (rpm)	-0.00488389	-0.00143899	0.000104908	2.18474	-2.49359	3.4359	-0.306509	0.0353609	-0.0011723	-0.0100651	-0.0072128	-0.00163365	-0.0036886	-0.0251604	-0.715561	-0.00046234
D: MD (%)	3.47043	11.5246	0.558561	4721.88	-3257.89	13717.7	-391.6	12.0241	-3.63568	-20.3048	-7.56697	3.42134	-0.0046178	-7.25601	428.628	39.816
AA	-0.00789666	0.0125486	0.00026879	1.30524	-8.7628	4.54443	0.206618	0.0221361	-0.011079	0.0103853	0.00800197	0.00120261	-0.0219013	-0.0298758	-0.46072	0.0308066
AB	0.0063625	0.0201525	-0.000895	6.09423	-9.24072	2.0501	-0.00045	-0.07388	0.002745	-0.002	0.005055	0.0095	0.0075	-0.00275	-0.014	-0.090847
AC	2.41875E-06	1.93937E-05	7.00E-07	0.00708569	-0.00067094	0.001537	0.00002625	0.0000711	4.9025E-05	1.0638E-05	-9.4125E-06	-3.4375E-06	0.00004625	7.8125E-05	0.00079125	-1.6661E-05
AD	0.00048125	-0.0217438	-0.0015	-10.3194	-13.9932	-79.5882	1.849	0.0061625	0.224175	0.148938	0.0726125	-0.022975	0.07	0.118125	-3.0275	0.138589
BB	0.0152534	-0.0166257	-0.00027248	17.9618	21.8016	19.3475	-2.32613	-0.0004558	0.113764	-0.00839873	-0.0573921	-0.0138696	0.0803949	0.0644968	1.07312	-0.19168
BC	-1.25E-08	4.25875E-05	-1.425E-06	-0.00733563	-0.0288496	-0.00219875	0.0020495	0.000172825	0.00008605	3.8625E-05	-0.000007	-0.00000745	0.000005	-0.00000875	0.00008	-8.0328E-05
BD	-0.0221875	-0.117488	-0.005125	-15.5444	65.8354	-25.9462	0.01425	-0.4799	-0.32665	0.059025	-0.02375	-0.002875	-0.1425	-0.09375	1.0825	-1.1
CC	1.14E-07	-1.12E-07	-2.08E-09	-5.0317E-05	0.000106724	-7.8774E-05	2.91171E-06	-1.3871E-06	-3.14E-07	1.36E-07	2.11E-07	5.79E-08	-9.75E-08	3.16E-07	1.3757E-05	1.40E-07
CD	-8.0031E-05	9.30937E-05	2.50E-07	-0.0557641	0.0308666	-0.00148687	0.00262437	0.000641625	0.00033381	0.00000325	-4.0375E-05	1.375E-06	0.00015625	0.00014063	0.00065	0.0004361
DD	-0.0035414	-0.138286	-0.00045303	-70.0391	-59.8889	-120.182	6.7642	0.678526	-0.705975	-0.266992	0.0796744	-0.0129347	-0.147532	-0.321895	-11.0055	0.773739

(128-132 °C). The antioxidant activity of Andean blackberry may be mainly associated with its phenol content and anthocyanins; the concentration of these compounds was affected differently by the variables associated with the SD process. Phenols were more affected by thermal stress than anthocyanins; however, MD offered protection for both compounds. Horvitz *et al.* (2017) found that there was no significant correlation between total phenols and antioxidant activity in blackberry extracts. Antioxidant activity, in addition to the anthocyanins, could be related to the Andean blackberry's other phenolic compounds such as ellagitannins and ellagic acid derivatives, followed by minority phenols such as flavonols and phenolic acids (gallic, caffeic, coumaric, and ferulic) (Schulz & Chim, 2019).

Several authors have investigated the effect of spray drying on the activity of the ABTS radical: Franceschinis *et al.* (2014) reported 38.4 and 33.3% anti-radical activity in blackberry powder encapsulated with MD and MD+Trealosa, respectively at 175 °C IAT. Pereira *et al.* (2019) reported ABTS antioxidant capacity in juçara powder ($859 \pm 44 \mu\text{mol Trolox/g bs}$) at 160°C IAT and 86 °C OAT. For this, protein and carbohydrates had a protective effect against the degradation of the active components.

Although the antioxidant activity of BPLI measured by the DPPH method did not show significant statistical differences (Table 2), it showed a tendency to increase mainly due to the decrease in OAT that increases the values of antioxidant activity (Figure 1d). Compared to other research, the DPPH results obtained for BPLI were similar to values reported by Da Fonseca-Machado *et al.* (2018) ($109.5 \pm 3.82 \mu\text{mol Trolox/g bs}$) who encapsulated extracts rich in anthocyanins from blackberry residues through SD. Moreover, Ferrari *et al.* (2013) reported DPPH values in blackberry powder that had different levels of encapsulants: 7% MD, 7% GA, and 3.5% MD+3.5% GA, that were 210; 250; 240 $\mu\text{mol Trolox/g bs}$, respectively, which, established that the protein fraction of the GA contributed to Maillard's reaction and therefore to the increase of the antioxidant activity.

SD process optimization

The experimental optimization process was carried out considering all the dependent variables as objective functions. Those variables that had statistically significant differences in the process were considered to have greater weight and impact: viability, S, H, L*, a*, TP, ABTS, and anthocyanins (Table 2).

The result of the optimization of multiple responses was a 71.9% desirability, and the independent variables of the SD process were set as such: IAT: 121 °C, OAT: 71.6 °C, ADS: 24000 rpm, and MD: 5%. Table 3 illustrates the criteria, weights, and impacts considered, as well as the experimental values obtained from 3 replicas of the optimal condition and the values predicted by the 2° order polynomial models that were adjusted to the response surface. Residual errors were considered acceptable with values $\leq 20\%$ (viability, M, TP, S, H, L*, a*, b*, D10, D50, and D90). Moreover, Table 4 shows the regression coefficients obtained from the optimization process in this work. However, the variables associated with antioxidant capacity (DPPH, ABTS, and anthocyanins) were the ones that showed the greatest deviation from the predicted values, mainly due to greater instability and variability with respect to process temperatures. On the other hand, the large number of dependent variables considered does not favour all the established criteria being fulfilled. Experimental optimization in SD processes has been effectively applied in Jamun powder (*Syzygium cumini* L.) (Singh *et al.*, 2019) and in the microencapsulation of probiotics in raspberry (Olivares *et al.*, 2019).

Conclusions

This study successfully established the optimal drying conditions for obtaining a powdered biofortified blackberry concentrate, which were as follows: IAT 121.1 °C, OAT 71.6 °C, maltodextrine proportion 5% (w/w), and ADS 24000 rpm. Results indicated that low OAT had the most significant impact on the response variables analyzed. Furthermore, spray drying allowed the production of a food product with probiotic properties obtaining $5.60 \times 10^7 \text{ CFU/g}$ that meets the standards set by both the USA and Colombia (10^6 CFU/g). This product, known as BPLI, not only possesses antioxidant activity and desirable physicochemical properties for stable powdered products, but also offers the modern consumer the benefits of probiotics and antioxidants. Additionally, the powder can also be considered a prebiotic product thanks to its content of both inulin and MD.

Data availability

Underlying data

figshare: Results of biofortified blackberry powder. <https://doi.org/10.6084/m9.figshare.22332553.v3> (Marin Arango *et al.*, 2023)

Data are available under the terms of the [Creative Commons Attribution 4.0 International license](#) (CC-BY 4.0).

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