



HAL
open science

Encapsulation of curcumin in milk powders by spray-drying: Physicochemistry, rehydration properties, and stability during storage

Maria Isabel Landim Neves, Sylvie Desobry-Banon, Italo Tuler Perrone, Stephane Desobry, Jérémy Petit

► To cite this version:

Maria Isabel Landim Neves, Sylvie Desobry-Banon, Italo Tuler Perrone, Stephane Desobry, Jérémy Petit. Encapsulation of curcumin in milk powders by spray-drying: Physicochemistry, rehydration properties, and stability during storage. *Powder Technology*, 2019, 345, pp.601-607. 10.1016/j.powtec.2019.01.049 . hal-02128005

HAL Id: hal-02128005

<https://hal.univ-lorraine.fr/hal-02128005>

Submitted on 21 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

38 **ABSTRACT**

39 Curcumin is a natural polyphenol that has strong antioxidant, anti-inflammatory and
40 anti-carcinogenic properties, however, it is sensitive to light, oxygen and heat, and also
41 presents very low solubility in water. Several studies have focused on curcumin
42 preservation and bioavailability due to its health importance, especially by
43 encapsulation. Milk may constitute a good matrix for the encapsulation of curcumin,
44 because it contains a significant proportion of casein micelles which are amphiphilic
45 and porous, making them suitable for carrying hydrophobic substances such as
46 curcumin. This work aims at evaluating the efficiency of milk for encapsulating
47 curcumin, releasing it in an aqueous medium during powder reconstitution, and
48 improving its preservation during storage. Curcumin was encapsulated by spray-drying
49 at pilot scale, extracted by different solvents, and quantified by UV/Vis.
50 spectrophotometry. Physicochemical characteristics (particle size distribution, water
51 content, water activity, and color) and rehydration properties (wettability, dispersibility,
52 and solubility indices) of curcumin-loaded milk powder were characterized. A powder
53 storage study was also conducted to evaluate the stability of curcumin over time at
54 different temperatures (10, 25 and 50 °C). Drying conditions were set to obtain a
55 product of water activity close to 0.2. A method for curcumin extraction and dosage was
56 also validated using diethyl ether as extraction solvent. Milk powder loaded with
57 curcumin showed no significant differences in most characteristics compared to raw
58 milk powder, except that its wettability was decreased by the presence of curcumin.
59 Moreover, the good encapsulation yields and the stability of curcumin antioxidant
60 activity during storage showed the suitability of skim milk for curcumin encapsulation.

61 **Keywords:** curcumin; antioxidant activity; encapsulation; skim milk; storage stability;
62 color.

63

64 **1. Introduction**

65 Curcumin is a bioactive polyphenol extracted from turmeric rhizome (*Curcuma*
66 *longa*) [1] that has anti-inflammatory, antimicrobial, anti-amyloid, and antitumor
67 properties. Polyphenols present antioxidant activity, hence they are prone to induce
68 beneficial effects on human health [2]. Curcumin is known to present a very low
69 solubility in water (2.99×10^{-8} M), a characteristic that limits its use in food products,
70 especially in aqueous solutions [1, 3]. Besides, its sensitivity to environmental
71 conditions, including elevated temperatures, light, extreme pH, moisture, and oxygen,
72 makes curcumin susceptible to degradation during processing and storage [2]. Thus,
73 several studies have been carried out aiming at developing techniques for its protection
74 in food products [2, 4, 5, 6, 7, 8, 9]. Microencapsulation is a commonly used technique
75 to stabilize and protect bioactive compounds in microscopic particles. With this
76 technique, a micro/nano environment is created, incorporating unstable ingredients
77 within a carrier matrix and developing a protection to the external environment [10].
78 Encapsulation provides protection against degradation reactions and prevents the loss of
79 flavor, nutrients, and/or bioactive compounds. In addition, it can be used to limit the
80 release of components during food processing and storage, while controlling the release
81 rate in physiological (gastric, intestinal) conditions [7, 11, 12, 13, 14, 15, 16]. Numerous
82 methods of microencapsulation exist: spray-drying, spray chilling/cooling,
83 coacervation, extrusion, fluidized bed coating, liposome entrapment, and molecular
84 inclusion [2]. Spray-drying surely represents the most commonly used encapsulation
85 technique, owing to its many advantages:

- 86 - it is economical: around ten times cheaper than the lyophilization process;
- 87 - versatile: various configurations of air and spray flows exist (co-current,
88 counter-current, or combined flows), and the spray can either be produced by a
89 centrifugal atomizer or an atomizing nozzle;

90 - and it is suitable for meeting the quality and efficiency constraints of various
91 industrial fields such as pharmaceuticals, cosmetics, and food.

92 Generally, spray-dried powders have good techno functional properties like
93 good rehydration ability, high flowability and long shelf-life [17, 18]. Spray-drying is
94 especially useful for encapsulating various heat-sensitive food ingredients such as
95 polyphenols, flavonoids, anthocyanins, prebiotics, phytosterols and polysaccharides,
96 because the temperature increase in the matrix remains limited throughout the drying
97 process [2, 10, 19]. Indeed, during most of the drying time, the surface of the particle
98 remains wet and the local temperature of the surrounding air does not exceed its wet
99 temperature that is around 50 °C in classical spray-drying conditions [18].
100 Consequently, the alteration of heat-sensitive compounds remains limited [20].

101 Milk is an interesting matrix candidate for encapsulation by spray-drying [7],
102 owing to its structural and physicochemical properties: binding of ions and small
103 molecules, surface-active and self-assembly properties, possibility of gelation, pH-
104 dependent gel-swelling behavior, possibility to control matrix rehydration kinetics and
105 thus bioactive release, interactions with macromolecules to form complexes and
106 conjugates with synergistic combinations of properties, various shielding capabilities
107 that are essential for protecting sensitive encapsulated compounds, biocompatibility and
108 biodegradability, possibility to control the bioaccessibility of the bioactive and promote
109 its bioavailability [7, 8].

110 The protection efficiency of milk powders towards encapsulated bioactive
111 compounds is mastered by their main physicochemical properties, such as chemical
112 composition, particle size distribution, and particle shape factors. In particular,
113 granulometric characteristics (that can be deduced from particle size distribution) of a

114 powder is an important parameter because it influences many functional properties such
115 as flowability and rehydration capacity [17, 18, 21, 22, 23].

116 The ability to reconstitute milk from powder is an essential property for
117 industrials and consumers using powdered dairy ingredients or products. The
118 International Dairy Federation has defined three reconstitution indices, namely
119 solubility, dispersibility, and wettability indices [24, 25], that describe different steps of
120 powder rehydration and depend on powder composition and affinity between water and
121 its components, but also on particle size, shape, and structure (porosity) [18, 26, 27].

122 During the storage of dairy powders, several changes can be observed mainly
123 depending on storage temperature and powder water content. Dairy powders are
124 susceptible to undergo agglomeration and caking, which are known to alter various
125 powder characteristics like particle size distribution, rehydration ability, and color [26,
126 27, 28]. When employed as an encapsulation matrix, physicochemical and techno
127 functional properties of powdered milk must be kept as much as possible in order to
128 ensure and maintain maximum protection of the active material [2, 28, 19].

129 The objective of the current work was to produce a milk powder encapsulating
130 curcumin and study the evolution of degradation of curcumin powder during storage at
131 different temperatures. Then, spray-drying was performed to produce milk powders in
132 which curcumin is encapsulated. Physicochemical characteristics (particle size
133 distribution, moisture content, colorimetric properties) and rehydration behavior
134 (accessed by the wettability, dispersibility, and solubility indices) were evaluated for the
135 fresh powder. Encapsulation efficiency was also determined just after spray-drying.
136 Last, curcumin-loaded milk powder was stored at different temperatures (10, 25, and 50
137 °C) to determine the stability of curcumin upon aging.

138

139 **2. Material and methods**

140 2.1. Material

141 Skim milk powder “Lait spray 0 %”, used to prepare concentrates to be spray-
142 dried, was purchased from Ingredia (Arras, France); its moisture content was 3.5 %
143 (w/w). Curcumin powder (≥ 94 % purity) was purchased from Sigma-Aldrich (Saint-
144 Quentin Fallavier, France). All other chemicals, of analytical grade, were provided by
145 Carlo Erba (Milan, Italy).

146

147 2.2. Production of milk powders by spray-drying

148 The production of milk with and without curcumin was conducted by spray-
149 drying 810 g skim milk concentrates at 30 % dry extract. Curcumin was solubilized in
150 ethanol at maximum concentration ($1 \text{ mg}\cdot\text{mL}^{-1}$). The curcumin concentration in skim
151 milk concentrates was set at 0.083 mg/g milk powder (dry basis, d.b.) as the
152 concentration of ethanol in spray-dried concentrates should not exceed 2 % (w/w)
153 according to the spray-drying pilot specifications. The employed spray-dryer was a
154 Micra Spray MS150 (Anhydro, Soeborg, Danemark) with a co-current flow single
155 tower equipped with a bi-fluid nozzle (60 100 + Buffer Air Fluid 120, Spraying
156 System). The operating parameters were defined according to Perrone et al. [29] that
157 have studied the influence of drying parameters on water activity. The objective is to
158 obtain powders with a water activity lower than 0.2, which makes them less sensitive to
159 biochemical alterations during storage [29]. In this work, spray-dried skim milk
160 powders with curcumin and without curcumin will be noted LC and LS respectively.
161 Immediately after spray-drying, powders were stored at 10 °C in sealed polypropylene
162 bags. The spray-drying yield (%) was calculated by dividing the dry mass of produced
163 powder by the dry mass of spray-dried milk (810 g).

164 In order to regulate the outlet air temperature at 90 °C, the inlet air temperature
165 and the product flow rate needed to be adjusted, depending on weather conditions, as
166 inlet air humidity was not regulated (Table 1). A fan power of 70 % and a spray
167 pressure of 1 bar were maintained for all drying experiments.

168 According to Table 1, even if spray-drying conditions were close, significant
169 differences were denoted between the two spray-drying assays. Globally, the inlet air
170 temperature and the concentrate flow-rate of the second assay (LS2 and LC2) were a
171 little higher. In general, when the inlet flow is higher, the outlet temperature tends to be
172 lower, which could be seen in the second assay.

173

174 2.3. Curcumin extraction and dosage

175 First, it was found in preliminary studies (data not shown) that ethanol is the best
176 solvent for curcumin extraction; moreover, it is readily available and less dangerous
177 than other organic solvents. A wavelength of 425 nm was chosen for performing
178 curcumin quantification by UV-visible spectrophotometry.

179 Curcumin extraction was achieved according to the following procedure: 0.1 g
180 curcumin-loaded skim milk powder was solubilized in 5 mL distilled water using a
181 Stuart SB3 rotator for 50 min at 40 rpm at 25 ± 1 °C. Then, 10 mL diethyl ether was
182 added, and the mixture was allowed to stir in the same conditions. The mixture was then
183 centrifuged at 5 088 x g for 5 min with a Hereaus Megafuge 8R centrifuge (Thermo
184 Fisher Scientific) and the supernatant was recovered and placed under a dinitrogen
185 atmosphere until complete evaporation of diethyl ether. Finally, 1 mL ethanol was
186 added. The curcumin solution was diluted hundredfold before analysis by UV-Visible
187 spectrophotometry at 425 nm. Curcumin ethanolic solutions up to 0.1 mg/mL were
188 analyzed in the same conditions for calibration purposes.

189 The results are given in milligrams of curcumin per gram of skim milk powder
190 (d.b.) (mg/g), according to the following equation:

$$191 \quad \frac{m_c}{m_p} = [\text{Curc}]_{\text{powder}} \quad (\text{Equation 1})$$

192 And the proportion of spray-dried curcumin found in analyzed powder was
193 calculated according to:

$$194 \quad \%curcumin = \frac{[\text{Curc}]_{\text{powder}}}{[\text{Curc}]_{\text{conc}}} \cdot 100 \quad (\text{Equation 2})$$

195 Where m_p designates the mass of skim milk powder (d.b.) (g), m_c the mass of detected
196 curcumin (mg), $[\text{Curc}]_{\text{conc}}$ the curcumin concentration in the feed concentrate (0.083
197 mg/g dry mass of skim milk concentrate), and $[\text{Curc}]_{\text{powder}}$ the curcumin concentration
198 found in powders (in mg/g dry mass of skim milk powder).
199

200 2.4. Physicochemical properties of powders

201 2.4.1. Particle size distribution

202 The particle size distribution was measured using a Mastersizer 3000 laser
203 diffraction granulometer (Malvern Instruments), supplied with the Aero S dry
204 dispersion unit. To obtain a correct obscuration (1 %), samples were dispersed at 1.8 bar
205 air pressure, 100 % air pressure, 40 % feed rate, and 2.7 mm hopper length. The particle
206 size estimator was chosen as the volume mean diameter and the mean particle size d50
207 was defined as the diameter for which 50 % of analyzed particles have lower size [30].
208

209 2.4.2. Moisture content and water activity

210 The moisture content was determined by the AOAC method 925.10 [31]. The
211 water activity was determined with the water activity analyzer HygroPalm apparatus
212 (HP23-AW-A, Rotronic, Croissy-Beaubourg, France).
213

214 2.4.3. Colorimetry

215 Powder color was characterized with a Microflash 200D apparatus (Data color
216 International, Lawrenceville, USA). For each sample, 10 g powder was poured in a Petri
217 dish (leading to a powder layer of approximately 1 cm high) and color measurement
218 was performed according to the three colors coordinates L, a*, b* of CIEL*a*b*
219 system. The L* value represents sample luminosity, varying from black (0) to white
220 (100), the a* value represents the color varying from red (+) to green (-) and the b*
221 value represents the color varying from yellow (+) to blue (-) [28]. The chroma, that
222 defines the degree of color saturation, was calculated with the following formula: $C^* =$
223 $\sqrt{(a^{*2}+b^{*2})}$. Also, the hue angle (H*), derived from the two coordinates a* and b*, was
224 determined as $\arctan(b^*/a^*)$. All measurements were taken as the average of at least
225 three points on the center and the periphery of the Petri dish filled with powder samples.

226

227 2.5. Powder functionalities

228 The rehydration properties of milk powders are essential techno-functional
229 properties for application purposes. The rehydration behavior and kinetics of spray-
230 dried skim milk powders were characterized.

231

232 2.5.1. Rehydration behavior

233 The water solubility index was determined by the methodology described in [25,
234 18]. The wettability and dispersibility indices were measured according to [18]. The
235 solubility was calculated from the volume of sediment (mL) remaining after two
236 centrifugations. The procedure consists in adding 10 g powder in 100 mL distilled
237 water, stirring the mixture during 90 s at 3 800 rpm, letting it at rest for 15 min, then
238 stirring it briefly with a spatula and pouring it into the centrifuge for 5 min at 160 x g.

239 Fill the tube with water up to the 50 ml mark. Disperse the sediment in the water and
240 centrifuge again at 160g for 5 min. Note the quantity of sediment (ml). The insolubility
241 index (II) is equal to the volume of sediment (ml) remaining after the second
242 centrifugation from 50 ml of
243 reconstituted liquid. The solubility index (SI), expressed as a %, is equal to:

$$244 \quad SI = 100 - [2 \cdot II] \quad (\text{Equation 3})$$

245 Wettability analysis consists in measuring the time required for a powder sample
246 to cross water surface in given conditions: 100 mL distilled water was added into a 400-
247 mL beaker and then 10 g skim milk powder was gently poured at the water surface.

248 The dispersibility index is the percentage of powder mass which can pass
249 through 200- μ m mesh size sieve. 10 g skim milk powder was added to 100 g distilled
250 water, then the mixture was vigorously stirred with a spatula for 15 s. After that, the
251 mixture was sieved, and the dry extract of the filtrate was determined after drying at 105
252 °C for 7 h in an oven. The dispersibility index (DI), expressed as a %, is equal to:

$$253 \quad DI = \frac{(100+w) \cdot X_{DM}}{w \cdot \frac{100-X_{RM}}{100}} \quad (\text{Equation 4})$$

254 Where w is the weight of the powder used, X_{RW} is the residual free water content of the
255 powder (% w/w), X_{DM} is the dry matter of the filtrate after sieving (% w/w). Express the
256 result to one decimal place.
257

258 2.6. Powder aging during storage

259 The stability of encapsulated curcumin during storage was also evaluated.
260 Powder samples were stored at 10, 25, and 50 °C for 2 months in hermetically-sealed
261 plastic pots at 0.43 water activity by using a saturated solution of potassium carbonate
262 [32]. Qualitative analysis of curcumin by UV/visible spectrophotometry at 425 nm was
263 performed on aged powders after the extraction step.

264

265 2.7. Statistical analysis

266 Spray-dried powders were produced in duplicate and all the analyses were
267 triplicated. Statistical analysis (ANOVA to check the occurrence of significant
268 differences among samples and Tukey's HSD test to identify what samples were
269 significantly different) was carried out with STATISTICA 7.0 software (StatSoft) at $p <$
270 0.05.

271

272 **3. Results and discussion**

273 3.1 Spray-drying

274 Spray-dried powder amounts and yields obtained in the first and second spray-
275 drying assays were represented in table 2.

276 Powder yields were higher in the first spray-drying assay. In the second spray-
277 drying, environmental conditions led to a little reduction of the outlet air temperature,
278 which favored powder adhesion to spray-dryer walls [20, 27, 33]. Most losses during
279 spray-drying were due to particles adhering to the spray-dryer walls, but there was also
280 a proportion of very small particles that were not retained by the cyclone. In fact, there
281 is a relationship between the size of the particles and losses in the exhaust air: the
282 smaller the particles, the harder they can be recovered with a cyclone [33, 34].

283

284 3.2 Physicochemical properties

285 Physicochemical characteristics mean particle size, moisture content, water
286 activity, and colorimetric parameters (lightness L^* , chroma C^* and hue angle h^*) of
287 skim milk powders with and without curcumin were determined (Table 3).

288 Mean particle diameters of spray-dried powders were smaller than those found
289 in the literature for milk powders, even on the same pilot-scale plant [18, 21, 25, 30].

290 This could result from the presence of ethanol in skim milk concentrates, which was
291 used to solubilize curcumin. Indeed, viscosity of concentrates containing a small
292 proportion of ethanol is expected to be lowered, which is known to enhance the liquid
293 jet breakup, leading to smaller droplets and thus smaller particles [30, 32]. All spray-
294 dried powders presented very close mean diameters, showing that the presence of
295 curcumin did not impact the size of spray-dried particles.

296 All produced powders presented water contents close to 5 % (w/w), which is a
297 sign of a good storage ability of powders [18]. No significant difference was denoted
298 among powders with or without curcumin, whatever the spray-drying assay. Fang [2]
299 found that spray-dried powders present lower moisture content at higher temperatures,
300 which was also observed in the present study. The atmospheric conditions during the
301 second atomization were warmer and wetter, which also contributed to produce a wet
302 and adherent powder.

303 The spray-drying conditions significantly influenced the water activity of the
304 samples, as the powders produced during the first spray-drying assay had a slightly
305 lower water activity (0.12) than those of the second spray-drying assay (0.14). This
306 difference can be attributed to the higher feeding flow-rate of concentrate of the second
307 spray-drying assay, which led to lower temperature and probably a higher relative
308 humidity of outlet drying air [33, 34].

309 The introduction of curcumin in food powders is expected to change their color
310 by increasing their yellowness [35]. This was checked by colorimetric analysis (Table
311 3). Powder luminosity was significantly different for skim milk with and without
312 curcumin and for the two spray-drying assays. The presence of curcumin increased
313 powder lightness but also its chroma (representing the degree of color saturation),
314 showing that powders with curcumin were brighter and more colored. The main color of

315 all powders was greenish-yellow, even in the absence of curcumin. For skim milk
316 powders free from curcumin, this can be explained by the presence of riboflavin, a
317 yellowish-green colored milk compound.

318

319 3.3. Powder functionalities

320 Most food additives and ingredients are presented in powder form and must be
321 rehydrated before use; hence, water-powder interactions and more generally the ability
322 to reconstitute a powder in water are essential properties for the formulation of many
323 food products [18, 33]. Rehydration indices of produced skim milk with and without
324 curcumin are displayed in Table 4.

325 Skim milk powder in the absence of curcumin was poorly wettable (wettability
326 times ranging between 30 and 35 min), but upon curcumin addition, powder became not
327 wettable (wettability times superior to 45 min). Wettability was the only factor that
328 showed significant difference between skim milk powders with and without curcumin
329 whatever the spray-drying assay. Dispersibility and solubility of LS and LC differed in
330 the first spray-drying assay but were similar in the second one. This shows that a small
331 change in spray-drying conditions may have a tremendous impact on powder
332 functionalities. Indeed, it can be guessed that modifying the evaporation rate (mainly by
333 changing concentrate feed rate, drying air temperature or flow-rate) may have an impact
334 on the location of curcumin within skim milk particles, as more curcumin at the surface
335 of particles may affect their rehydration capacity, owing to the hydrophobicity of this
336 bioactive compound. This explanation is in accordance with the results of the first
337 spray-drying assay, where skim milk powder without curcumin exhibited lower
338 wettability and solubility but a better dispersibility. Moreover, it can be guessed that
339 curcumin addition modified powder surface structure. According to Murrieta-Pazos et

340 al. [27], the surface of skim milk powders is mainly covered by proteins. Due to the
341 interaction of curcumin with casein, modification of casein micelle conformation
342 probably occurred [34, 35, 36], which induced a change of the interaction sites of
343 caseins at the surface of particles and affected interactions of powder with water.

344 It is considered that a powder is dispersible when dispersibility index exceeds
345 85 % [18]. Therefore, spray-dried powders of the current study had low dispersibility.
346 Generally, a soluble powder is not very dispersible because it dissolves easily when
347 being in contact with water, so it does not separate into small particles but solubilizes
348 quickly in water [18, 33]. The high solubility of spray-dried powders is thus consistent
349 with their poor dispersibility. Also, producing powders at pilot scale results in low mean
350 particles size (see the d50 values around 15 μm , which is relatively small for food
351 powders) [37], and powders constituted by small particles have a tendency to be
352 cohesive [38] and thus hard to disperse.

353

354 3.4 Storage study

355 Sample color was followed during storage (Table 5 and Figure 1) with a view to
356 correlate colorimetric changes to the evolution of curcumin content in powders (Figure
357 2). Indeed, curcumin is yellow, and its alteration leads to color loss [39] or the
358 formation of degradation products having a more brownish/reddish color [40, 41].

359 As previously discussed from table 1 results, for all spray-dried powders, the
360 lightness at time zero was high. Furthermore, color saturation was higher in skim milk
361 powders containing curcumin, due the yellow color by curcumin. Also, the main color
362 of all powders was similar: greenish-yellow.

363 During storage, a decrease in powder lightness was observed for all samples and
364 this darkening phenomenon was more intense at 50 °C. At 10 and 25°C, the color

365 saturation remained unaffected in the course of storage, but at 50 °C color saturation
366 increased for powders without curcumin, while it slightly decreased for powders with
367 curcumin. Moreover, the hue angle showed a decrease at 50 °C, indicating a shift of
368 powders without curcumin to orange-yellow, while it remained similar all along the
369 storage for powders with curcumin. It can be guessed that at 50 °C, the decrease in
370 luminosity, increase in saturation and increase in angle hue corresponds to the formation
371 of brown pigments, due to the occurrence of the Maillard reaction. In fact, Maillard
372 reaction corresponds to a group of chemical reactions initiated by the condensation of
373 an amino group with a reducing sugar and resulting in the formation of brown
374 compounds [33].

375 The formation of brown pigments is evidenced by photographs displayed in
376 Figure 1: after 60 days storage at 50 °C, the color change was more pronounced for
377 skim milk powder without curcumin, hence the limitation of color change for LC
378 powders may be attributable to the presence of curcumin. This observation should be
379 put in relation with the antioxidant power of curcumin that improved powder
380 preservation during high-temperature storage, presumably by decreasing the kinetics of
381 the Maillard reaction.

382 Skim milk powders with curcumin tended to remain a little more yellow than
383 powders without curcumin [42], due that a significant proportion of curcumin was still
384 present after 60 days storage at 50 °C, as evidenced by curcumin quantification (Figure
385 2).

386 During storage, curcumin was more altered when stored at high temperature, as
387 expected for this thermolabile compound: about 83 %, 72 %, and 58 % residual
388 curcumin were found after 60 days storage at 10, 25, and 50 °C, respectively (Figure 2).
389 This demonstrates the importance of adequate conditioning and storage conditions to

390 avoid changes in powder characteristics and the amount of residual bioactive material
391 [26, 27, 28, 38, 39]. Encapsulation in dairy matrices may be a way to limit its
392 alteration, owing to the interaction with casein micelles [36] that can improve curcumin
393 stability [43].

394 The decrease in curcumin content was correlated to the decrease in yellow color:
395 indeed, the Pearson correlation coefficients between residual curcumin content and
396 color saturation were 0.64, 0.79, 0.82 for powders stored at 10, 25, and 50 °C,
397 respectively, showing a marked positive correlation whatever the storage temperature.
398 Thus, the variation in concentration of curcumin explains a large part of the evolution of
399 powder color during storage. The stronger correlation for powders stored at 50 °C may
400 be derived from the increase in curcumin degradation rate at this higher temperature
401 [44].

402

403 Figure 3 illustrates the link between chroma (C*) and curcumin content. It can
404 be noted that, whatever the storage temperature, both chroma and curcumin
405 concentration tended to decrease with storage time. Besides, storage temperature had a
406 negative effect on curcumin-loaded skim milk powder chroma and this can be put in
407 relation with the fact that low temperatures help maintain curcumin color [43, 44]. For
408 all temperatures, from 14 storage days, the decrease in curcumin content was
409 accompanied by a decrease in powder chroma and this phenomenon was more evident
410 at 10 °C. For all temperatures, between 28 and 42 days, the decrease in powder chroma
411 was more significant compared to the other storage times. It may be guessed that
412 curcumin alteration during storage begins with curcumin located at the powder surface,
413 which strongly affects powder color. Then, at longer storage times, curcumin hidden in
414 the powder bulk starts to be degraded, but without much affecting powder surface

415 appearance. Hence, the link between powder surface color saturation and curcumin
416 content may be more relevant at relatively short storage times. At 25 °C and especially
417 at 50 °C, for the higher storage times (approximately from 42 days), the positive
418 correlation between chroma and curcumin content became less evident, as at these
419 temperatures the powders were expected to undergo Maillard reaction, which results to
420 the formation of brown pigments, thus affecting powder color independently from the
421 degree of curcumin alteration. It can then be concluded that the relation between chroma
422 and curcumin content was not linear due the existence of other factors affecting powder
423 color.

424 This correlation between powder color and curcumin content is very interesting
425 for industrials, as they can use powder color as an indicator to easily and quickly
426 evaluate the degree of curcumin alteration upon storage.

427 This study permitted to show that the presence of curcumin in spray-dried skim
428 milk powders did not significantly affect their main physicochemical characteristics,
429 except color, which was obviously more yellow in curcumin-loaded powders, and color
430 stability, which was improved by curcumin. Differences found among investigated
431 powders were more related to small changes in spray-drying conditions. It was also
432 suggested that Maillard reaction could be limited during storage (even at temperature as
433 high as 50 °C) by addition of a small curcumin proportion in dairy powder formulation.
434 Also, it was noted that curcumin alteration upon storage at high temperature remained
435 limited and this can be explained by the protective role of the dairy matrix against
436 curcumin oxidation. Previous studies with milk proteins have shown that milk proteins
437 (especially casein micelles) can substantially contribute to the protection of bioactive
438 compounds like curcumin by forming complexes with these molecules through
439 hydrophilic and/or hydrophobic interactions [7, 13, 40, 43].

440

441 **4. Conclusion**

442 This study dealing with encapsulation of curcumin in skim milk powder by
443 spray-drying permitted to evidence the impact of small changes in spray-drying
444 conditions, as well as the presence of curcumin on physicochemical and functional
445 properties of resulting powders. Spray-drying yield was slightly affected by minor
446 variations of spray-drying conditions. In the second spray-drying assay, the air outlet
447 temperature was a little lower, which increased particle adhesion to the spray-dryer
448 walls and slightly decreased process yield. This also impacted powder water activity:
449 powders of the second assay had a slightly higher water activity, consistently with the
450 lower air outlet temperature. Variations in spray-drying conditions between the two
451 assays were so close that other physicochemical (mean particle size, span, moisture
452 content) and functional (wettability, dispersibility, solubility) properties were similar.

453 The presence of curcumin in milk did not affect the spray-drying yield.
454 Physicochemical characteristics (mean particle size, span, moisture content, and water
455 activity) were also unchanged due to the presence of curcumin with the notable
456 exception of powder color. Indeed, curcumin-loaded powders were more bright (higher
457 luminance L^*) and had a higher saturation of yellow color (higher chroma C^* for a hue
458 angle h^* corresponding to yellow). As regards powder functional properties related to
459 reconstitution properties, solubility and dispersibility were unaltered by the presence of
460 curcumin, contrarily to wettability which was markedly lowered in the presence of
461 curcumin. Indeed, this hydrophobic compound may be found at powder surface,
462 decreasing interactions between powder surface and water, thus making it less wettable.

463 During storage, changes in color were observed: color saturation decreased,
464 indicating a decrease in powder yellowness. The color loss was enhanced when storage

465 temperature was increased. Color loss was correlated with the decrease in curcumin
466 concentration, hence powder color may constitute an indicator for following the degree
467 of alteration of curcumin encapsulated in dairy powders. For all studied temperatures,
468 the decrease in curcumin content during storage was low (28 % loss after 6 months
469 storage at 25 °C), showing the suitability of skim milk as an encapsulation matrix for
470 protecting curcumin.

471 This study allowed verifying the possibility of relating, during storage, the
472 evolutions of curcumin content and powder color saturation (chroma). It permitted to
473 highlight the negative effect of storage temperature on curcumin content. As a
474 perspective of this study, it would be interesting to evaluate the evolution of antioxidant
475 activity of curcumin-loaded milk powders upon storage in order to investigate if
476 curcumin keeps its antioxidant power when encapsulated in milk powders and stored.

477

478 **Acknowledgements**

479 The authors acknowledge the Coordenação de Aperfeiçoamento de Pessoal de Nível
480 Superior (CAPES) in Brazil for financial support and the LIBio laboratory in France for
481 scholarship and technical support.

482

483 **References**

484 [1] R. A. Sharma, A. J. Gescher, W. P. Steward, Curcumin: the story so far, European
485 journal of cancer 41(13) (2005) 1955-1968.

486

487 [2] Z. Fang, B. Bhandari, Effect of spray drying and storage on the stability of bayberry
488 polyphenols, Food Chemistry 129 (3) (2011) 1139-1147.

489

490 [3] B. Joe, M. Vijaykumar, B. R. Lokesh, Biological properties of curcumin – cellular
491 and molecular mechanisms of action, Critical Reviews in Food Science Nutrition 44
492 (2004) 97-111.

493

494 [4] A. Sahu, N. Kasoju, U. Bora, Fluorescence study of the curcumin – casein micelle
495 complexation and its application as a drug nanocarrier to cancer
496 cells, Biomacromolecules 9 (10) (2008) 2905-2912.

- 497
498 [5] F. Donsi, M. Sessa, H. Mediouni, A. Mgaidi, G. Ferrari, Encapsulation of bioactive
499 compounds in nanoemulsion-based delivery systems, *Procedia Food Science* 1 (2011)
500 1666-1671.
501
- 502 [6] L. Mazzarino, C. Travelet, S. Ortega-Murillo, I. Otsuka, I. Pignot-Paintrand, E.
503 Lemos-Senna, R. Borsali, Elaboration of chitosan-coated nanoparticles loaded with
504 curcumin for mucoadhesive applications, *Journal of colloid and interface science* 370
505 (1) (2012) 58-66.
506
- 507 [7] D.Y. Livney, Milk proteins as vehicles for bioactives, *Current Opinion in Colloid &*
508 *Interface Science* 15 (1) (2010) 73-83.
509
- 510 [8] A. Tsali, A. M. Goula, Valorization of grape pomace: Encapsulation and storage
511 stability of its phenolic extract, *Powder Technology* 340 (2018) 197-207.
- 512 [9] M. Hasan, N. Belhaj, H. Benachour, M. Barberi-Heyob, C.J.F. Kahn, E. Jabbari, M.
513 Linder, E. Arab-Tehrany, Liposome encapsulation of curcumin: physico-chemical
514 characterizations and effects on MCF7 cancer cell proliferation, *International journal of*
515 *pharmaceutics* 461 (1) (2014) 519-528.
- 516 [10] Z. Fang, B. Bhandari, Encapsulation of polyphenols—a review, *Trends in Food*
517 *Science & Technology* 21 (10) (2010) 510-523.
- 518 [11] A. Soottitantawat, H. Yoshii, T. Furuta, M. Ohkawara, P. Linko,
519 Microencapsulation by spray drying: Influence of emulsion size on the retention of
520 volatile compounds, *J. Food Sci.* 68 (2003) 2256-2262.
- 521 [12] A. Madene, M. Jacquot, Flavour encapsulation and controlled release – a review,
522 *Int. J. Food Sci. Tech.* 41 (2006) 1-21.
- 523 [13] S. R. Yazdi, M. Corredig, Heating of milk alters the binding of curcumin to casein
524 micelles: A fluorescence spectroscopy study, *Food chemistry* 132 (3) (2012) 1143-
525 1149.
- 526 [14] M. Corgneau, J. Scher, L. Le. D. T. Ritie-Pertusa, J. Petit, Y. Nikolova, S. Banon,
527 C. Gaiani, Recent advances on lactose intolerance: Tolerance thresholds and currently
528 available answers, *Critical reviews in food science and nutrition* 57 15 (2017) 3344-
529 3356.
530
- 531 [15] M. Corgneau, Développement de formulations alimentaires diététiques adaptées
532 aux intolérants au lactose et présentant une meilleure digestibilité, PhD Thesis, Ecole
533 Nationale Supérieure d' Agronomie et des Industries Alimentaires, France, 2016.
534
- 535 [16] Y. Nikolova, Développement de matrices permettant de protéger des substances
536 actives lors d'un traitement thermique, PhD Thesis, Ecole Nationale Supérieure d'
537 Agronomie et des Industries Alimentaires, France, 2017.

- 538 [17] Y. Nikolova, J. Petit, A. Gianfrancesco, C.F.W. Sanders, J. Scher, C. Gaiani,
539 Impact of spray-drying process parameters on dairy powder surface composition and
540 properties, *Drying technology* 33(13) (2015) 1654-1661.
- 541 [18] P. Schuck, R. Jeantet, A. Dolivet, *Analytical methods for food and dairy powders*.
542 John Wiley & Sons, 2012.
- 543 [19] S. Ray, U. Raychaudhuri, R. Chakraborty, An overview of encapsulation of active
544 compounds used in food products by drying technology, *Food Bioscience* 13 (2016) 76-
545 83.
- 546 [20] I. Filková, A.S. Mujumdar, *Industrial Spray Drying Systems*. Chapter 9, In:
547 *Handbook of Industrial Drying*, second edition, Vol. 1, Ed. A. S. Mujumdar, 1995 pp.
548 263-308.
- 549 [21] J. Toro-Sierra, J. Schumann, U. Kulozik, Impact of spray-drying conditions on the
550 particle size of microparticulated whey protein fractions, *Dairy science & technology* 93
551 (4-5) (2013) 487-503.
- 552 [22] X. Fu, D. Huck, L. Makein, B. Armstrong, U. Willen, T. Freeman, Effect of
553 particle shape and size on flow properties of lactose powders, *Particuology* 10 (2)
554 (2012) 203-208.
- 555 [23] P. Juliano, G.V. Barbosa-Cánovas, Food powders flowability characterization:
556 theory, methods, and applications, *Annual review of food science and technology*, 1
557 (2010) 211-239.
- 558 [24] *GEA* [https://www.gea.com/fr/binaries/A%205%20b%20-
559 %20Wettability%20IDF%20Method_tcm29-30910.pdf](https://www.gea.com/fr/binaries/A%205%20b%20-%20Wettability%20IDF%20Method_tcm29-30910.pdf) (Accessed: 15.02.2018).
- 560 [25] FIL (Fédération Internationale Laitière), *Détermination de la dispersibilité et de la*
561 *mouillabilité*, Brussels, Belgium, 1985.
- 562 [26] C. Gaiani, P. Boyanova, R. Hussain, I.M. Pazos, M.C. Karam, J. Burgain, J. Scher,
563 Morphological descriptors and color as a tool to better understand rehydration
564 properties of dairy powders, *International Dairy Journal*, 21(7) (2011) 462-469.
- 565 [27] I. Murrieta-Pazos, C. Gaiani, L. Galet, R. Calvet, B. Cuq, J. Scher, Food powders:
566 Surface and form characterization revisited, *Journal of food engineering* 112 (1) (2012)
567 1-21
- 568 [28] *Colour in food: improving quality*, ed. D. B. MacDougall, Woodhead Publishing, Boca
569 Raton, Fla., CRC Press Cambridge, 2002.
- 570 [29] I.T. Perrone, M. Simeao, P.H.R. Junior, R. Stephani, A.F. de Carvalho, Influence
571 of pilot spray dryer settings on moisture and water activity of whole milk powder, *Rev.*
572 *Inst. Laticínios Cândido Tostes* 68 (2013) 5-9.

- 573 [30] J. Petit, S. Méjean, P. Accart, L. Galet, P. Schuck, C. Le Floch-Fouéré, R. Jeantet,
574 A dimensional analysis approach for modelling the size of droplets formed by bi-fluid
575 atomization, *Journal of Food Engineering* 149 (2015) 237-247.
- 576 [31] AOAC (Association of Official Analytical Chemists). (1990). *Official methods of*
577 *analysis (13th edition.)* Washington, D.C: Association of Official Analytical Chemists.
- 578 [32] S. Mandato, E. Rondet, G. Delaplace, A. Barkouti, L. Galet, P. Accart, B. Cuq,
579 Liquids' atomization with two different nozzles: Modeling of the effects of some
580 processing and formulation conditions by dimensional analysis, *Powder technology* 224
581 (2012) 323-330.
- 582 [33] C. Gaiani, *Etude des mécanismes de réhydratation des poudres laitières: influence*
583 *de la structure et de la composition des poudres*, PhD Thesis, Ecole Nationale
584 Supérieure d' Agronomie et des Industries Alimentaires, France, 2006.
- 585 [34] B. Cuq, C. Gaiani, C. Turchiuli, L. Galet, J. Scher, R. Jeantet, S. Mandato, J. Petit,
586 I. Murrieta-Pazos, A. Barkouti, P. Schuck, E. Rondet, M. Delalonde, E. Dumoulin, G.
587 Delaplace, T. Ruiz, *Advances in food powder agglomeration engineering*, in:
588 Jeyakumar Henry, *Advances in Food and Nutrition Research*, Burlington: Academic
589 Press, 2013, pp. 41-103.
- 590 [35] M. Rajasekaran, J. Annaraj, A lucid build-up of nanostructured curcumin,
591 quercetin and their interaction with DNA, *Journal of nanoscience and*
592 *nanotechnology* 14 (7) (2014) 4874-4879.
- 593 [36] A. N. Khanji, F. Michaux, J. Petit, D. Salameh, T. Rizk, J. Jasniewski, S. Banon,
594 Structure, gelation, and antioxidant properties of curcumin-doped casein micelle powder
595 produced by spray-drying, *Food & function* 9 (2018) 971-981.
- 596 [37] E. H. Gnagne, J. Petit, C. Gaiani, J. Scher, G. N. Amani, Characterisation of flow
597 properties of foutou and fofou flours, staple foods in West Africa, using the FT4
598 powder rheometer, *Journal of Food Measurement and Characterization* 11 3 (2017)
599 1128-1136.
- 600 [38] S. Chever, S. Mejean, A. Dolivet, F. Mei, C.M. Den Boer, G. Le Barzic, R. Jeantet,
601 P. Schuck, Agglomeration during spray drying: Physical and rehydration properties of
602 whole milk/sugar mixture powders, *LWT-Food Science and Technology* 83 (2017) 33-
603 41.
- 604 [39] M. Kharat, Z. Du, G. Zhang, D. J. McClements, Physical and chemical stability of
605 curcumin in aqueous solutions and emulsions: Impact of pH, temperature, and
606 molecular environment, *Journal of agricultural and food chemistry* 65 (8) (2017) 1525-
607 1532.
- 608 [40] K. I. Priyadarsini, The chemistry of curcumin: from extraction to therapeutic
609 agent, *Molecules* 19 (12) (2014) 20091-20112.

- 610 [41] H. Tennesen, J. Karlsen, Studies on curcumin and curcuminoids. V. Alkaline
611 degradation of curcumin Z. Lebensm. Unters, Forsch 180 (2) (1985) 132-134.
- 612 [42] S. Wang, F. Ye, F. Wei, G. Zhao, Spray-drying of curcumin-loaded
613 octenylsuccinated corn dextrin micelles stabilized with maltodextrin, Powder
614 Technology 307 (2017) 56-62.
- 615 [43] O. Naksuriya, M. J. van Steenberg, J. S. Torano, S. Okonogi, W. E. Hennink, A
616 kinetic degradation study of curcumin in its free form and loaded in polymeric
617 micelles, The AAPS journal 18 (3) (2016) 777-787.
- 618
- 619 [44] S. S. PENYIMPANAN, Stability of curcumin in turmeric oleoresin- β -cyclodextrin
620 inclusion complex during storage, Malaysian Journal of Analytical Sciences 13 (2)
621 (2009) 165-169.

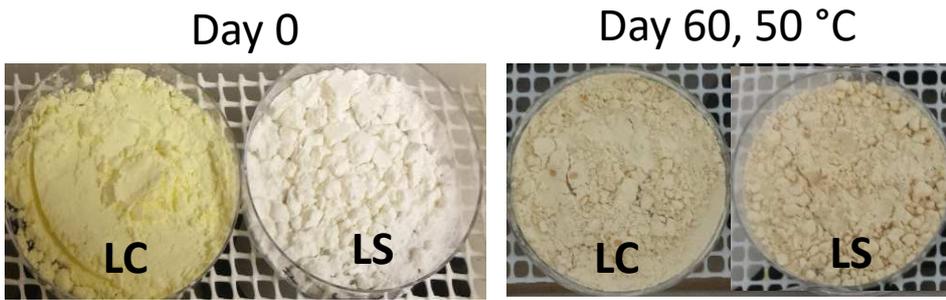


Figure 1. Skim milk powders with (LC) and without curcumin (LS), at fresh state and after 60 days storage at 50 °C.

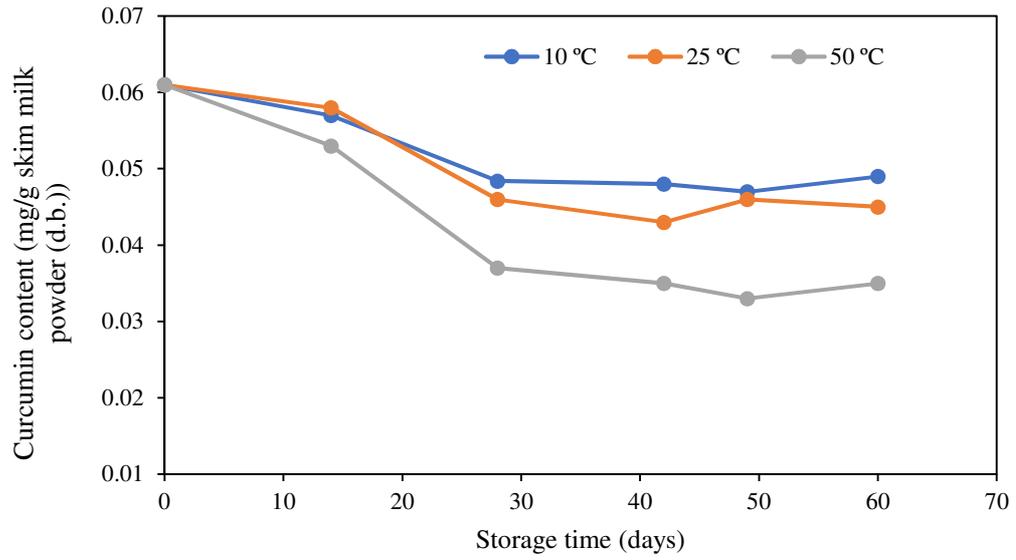


Figure 2. Evolution of curcumin content in spray-dried skim milk powders after 60 days storage at 10, 25, and 50 °C.

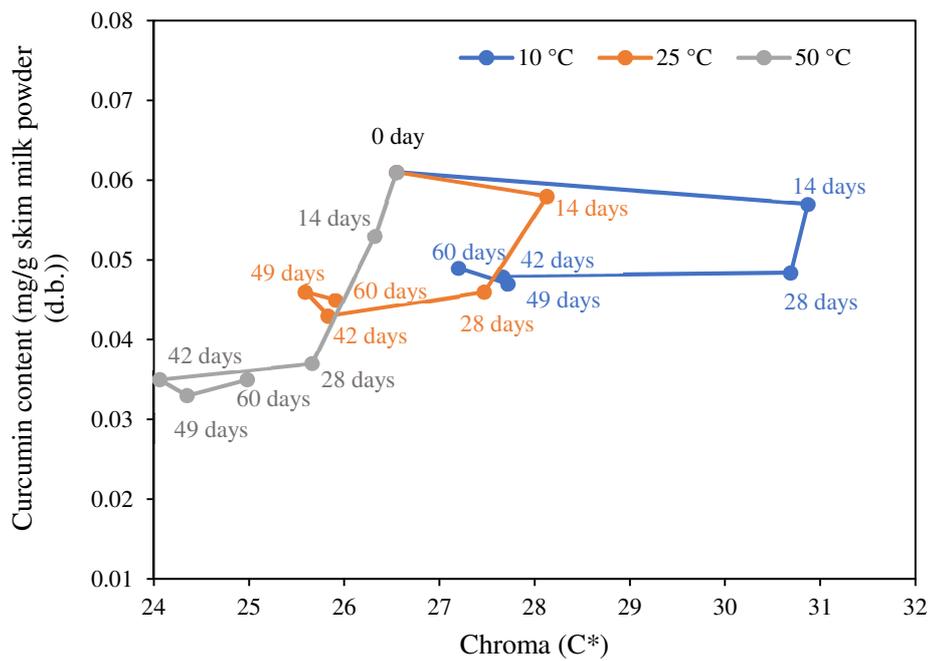


Figure 3. Relation between curcumin content in spray-dried skim milk powders and chroma (C*) after 60 days storage at 10, 25, and 50 °C.

Table 1. Spray-drying conditions for the production of skim milk powders with (LC1 and LC2) or without curcumin (LS1 and LS2). T_e = inlet temperature; T_s = outlet temperature; Q_L = skim milk concentrate flow rate.

	T_e (°C)	T_s (°C)	Q_L (mL/min)
LS1	161.6 ± 2.1 ^a	91.6 ± 1.2 ^b	35.0 ± 2.4 ^a
LC1	165.3 ± 1.2 ^c	92.2 ± 0.5 ^b	40.0 ± 0.0 ^b
LS2	164.4 ± 1.5 ^{bc}	88.6 ± 0.8 ^a	50.0 ± 1.4 ^c
LC2	162.8 ± 1.3 ^{ab}	88.8 ± 0.5 ^a	52.0 ± 0.0 ^c

Values in the same row followed by the same superscripted letters did not significantly differ according to Tukey's HSD test ($p < 0.05$).

Table 2: Mass of spray-dried powders and yields for the two spray-drying assays.

	Powder mass (g)	Yield (%)
LS1	598,25	74
LC1	685,06	85
LS2	548,84	68
LC2	562,27	69

Table 3. Physicochemical characteristics of skim milk powders with and without curcumin obtained by spray-drying.

	d50 (μm)	Moisture (% (w/w))	Water activity (-)	L* (-)	C* (-)	h* (-)
LS1	14.10 \pm 0.01 ^a	4.80 \pm 0.17 ^a	0.12 \pm 0.00 ^a	94.12 \pm 0.03 ^b	7.23 \pm 0.04 ^a	100.22 \pm 0.24 ^a
LC1	15.20 \pm 0.01 ^c	5.58 \pm 0.17 ^a	0.12 \pm 0.00 ^a	98.06 \pm 0.04 ^d	26.55 \pm 0.10 ^b	100.52 \pm 0.38 ^a
LS2	14.91 \pm 0.07 ^b	5.43 \pm 0.39 ^a	0.14 \pm 0.02 ^b	93.39 \pm 0.08 ^a	7.31 \pm 0.09 ^a	100.30 \pm 0.28 ^a
LC2	15.03 \pm 0.03 ^b	5.23 \pm 0.42 ^a	0.14 \pm 0.00 ^b	97.39 \pm 0.05 ^c	27.61 \pm 0.07 ^c	100.46 \pm 0,05 ^a

Values in the same column followed by the same superscripted letters did not significantly differ according to Tukey's HSD test ($p < 0.05$).

Table 4. Rehydration indices (wettability time, solubility and dispersibility) of skim milk powders with and without curcumin produced in the two spray-drying assays.

	Wettability (min)	Solubility (%)	Dispersibility (%)
LS1	35.75 ± 1.66 ^a	89.61 ± 0.34 ^a	37.52 ± 1.86 ^b
LC1	> 45	95.77 ± 0.57 ^b	27.60 ± 2.43 ^a
LS2	31.55 ± 0.76 ^a	96.17 ± 0.74 ^b	35.52 ± 1.02 ^b
LC2	> 45	95.96 ± 0.76 ^b	33.86 ± 1.39 ^b

Values in the same row followed by the same superscripted letters did not significantly differ according to Tukey's HSD test ($p < 0.05$).

Table 5. Evolution of powder colorimetry over 60 days storage.

		Day 0			Day 14			Day 28		
		L*	C*	h*	L*	C*	h*	L*	C*	h*
10 °C	LS1	94.12 ± 0.03	7.23 ± 0.04	100.22 ± 0.23	94.78 ± 0.14	6.76 ± 0.39	100.99 ± 0.94	94.41 ± 0.22	6.25 ± 0.29	101.51 ± 0.66
	LC1	98.06 ± 0.04	26.55 ± 0.10	100.52 ± 0.38	95.6 ± 0.34	30.87 ± 0.15	99.13 ± 0.02	95.45 ± 0.09	30.69 ± 0.11	99.00 ± 0.18
	LS2	93.39 ± 0.08	7.31 ± 0.09	100.30 ± 0.28	94.81 ± 0.07	6.17 ± 0.06	102.21 ± 0.08	94.32 ± 0.49	6.99 ± 0.02	100.61 ± 1.00
	LC2	97.39 ± 0.05	27.61 ± 0.07	100.46 ± 0.05	98.38 ± 0.04	27.86 ± 0.22	100.35 ± 0.03	96.64 ± 0.54	28.62 ± 0.21	99.35 ± 0.45
25 °C	LS1	94.12 ± 0.03	7.23 ± 0.04	100.22 ± 0.23	94.52 ± 0.07	5.77 ± 0.11	100.82 ± 0.14	94.56 ± 0.21	6.18 ± 0.04	98.36 ± 0.21
	LC1	98.06 ± 0.04	26.55 ± 0.10	100.52 ± 0.38	97.23 ± 0.07	28.13 ± 0.05	100.17 ± 0.01	96.45 ± 0.49	27.47 ± 0.79	99.43 ± 0.50
	LS2	93.39 ± 0.08	7.31 ± 0.09	100.30 ± 0.28	94.46 ± 0.04	6.11 ± 0.03	102.81 ± 0.16	94.85 ± 0.06	7.33 ± 0.12	99.44 ± 0.15
	LC2	97.39 ± 0.05	27.61 ± 0.07	100.46 ± 0.05	98.84 ± 0.05	30.31 ± 0.36	100.03 ± 0.08	97.23 ± 0.29	31.75 ± 0.10	99.13 ± 0.02
50 °C	LS1	94.12 ± 0.03	7.23 ± 0.04	100.22 ± 0.23	91.85 ± 0.10	5.18 ± 0.02	82.76 ± 0.21	88.59 ± 0.40	17.61 ± 0.24	84.22 ± 0.08
	LC1	98.06 ± 0.04	26.55 ± 0.10	100.52 ± 0.38	94.27 ± 0.24	26.32 ± 1.09	93.57 ± 0.10	90.51 ± 0.06	25.66 ± 0.19	89.64 ± 0.14
	LS2	93.39 ± 0.08	7.31 ± 0.09	100.30 ± 0.28	92.77 ± 0.07	5.91 ± 0.11	103.91 ± 0.25	92.65 ± 0.28	13.66 ± 0.18	88.27 ± 0.03
	LC2	97.39 ± 0.05	27.61 ± 0.07	100.46 ± 0.05	97.25 ± 0.10	30.29 ± 0.84	100.09 ± 0.02	96.28 ± 1.01	27.88 ± 0.03	93.82 ± 0.09
		Day 42			Day 49			Day 60		
		L*	C*	h*	L*	C*	h*	L*	C*	h*
10 °C	LS1	91.56 ± 0.09	4.58 ± 0.07	101.75 ± 0.32	92.31 ± 0.25	4.39 ± 0.11	101.65 ± 0.19	92.13 ± 0.15	4.38 ± 0.10	101.06 ± 0.38
	LC1	92.30 ± 0.03	27.67 ± 0.25	98.67 ± 0.12	92.17 ± 0.35	27.72 ± 0.36	98.65 ± 0.086	91.93 ± 0.31	27.20 ± 0.34	99.02 ± 0.35
	LS2	90.59 ± 0.46	4.44 ± 0.06	99.98 ± 1.95	90.30 ± 0.41	4.37 ± 0.30	102.24 ± 0.72	91.37 ± 0.21	4.53 ± 0.15	101.94 ± 0.67
	LC2	93.64 ± 0.50	25.78 ± 0.04	99.41 ± 0.02	94.13 ± 0.06	25.76 ± 0.21	99.12 ± 0.84	95.00 ± 0.36	25.72 ± 0.19	99.47 ± 0.50
25 °C	LS1	94.50 ± 0.11	5.59 ± 0.09	98.19 ± 0.11	91.41 ± 0.04	9.38 ± 0.15	138.87 ± 1.14	91.83 ± 0.16	9.29 ± 0.17	136.74 ± 1.9
	LC1	95.20 ± 0.12	25.83 ± 0.07	99.23 ± 0.02	92.80 ± 0.21	25.59 ± 0.33	98.66 ± 0.21	90.90 ± 0.23	25.91 ± 0.23	98.43 ± 0.30
	LS2	94.79 ± 0.03	6.25 ± 0.03	97.63 ± 1.31	91.50 ± 0.20	5.93 ± 0.26	95.98 ± 0.38	91.03 ± 0.15	6.13 ± 0.10	95.86 ± 0.23
	LC2	95.15 ± 0.09	28.84 ± 0.13	99.09 ± 0.04	92.26 ± 0.15	27.08 ± 0.01	99.64 ± 0.12	89.86 ± 0.15	24.56 ± 0.30	99.77 ± 0.32
50 °C	LS1	85.81 ± 0.17	21.05 ± 0.13	84.31 ± 0.23	84.73 ± 0.45	21.56 ± 0.08	85.56 ± 0.42	21.66 ± 0.15	21.72 ± 0.15	86.04 ± 0.28
	LC1	87.15 ± 0.05	24.06 ± 0.01	87.98 ± 0.06	87.00 ± 0.51	24.35 ± 0.35	88.07 ± 0.98	24.97 ± 0.15	24.98 ± 0.15	88.03 ± 0.07
	LS2	88.34 ± 0.03	15.89 ± 0.06	86.50 ± 0.03	87.76 ± 0.32	15.56 ± 0.21	86.57 ± 0.09	15.80 ± 0.21	15.83 ± 0.20	86.70 ± 0.04
	LC2	87.93 ± 0.35	24.79 ± 0.14	90.73 ± 0.08	87.66 ± 0.32	24.90 ± 0.10	90.85 ± 0.02	24.84 ± 0.30	24.80 ± 0.30	90.97 ± 0.10

Graphical Abstract:

