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ORIGINAL RESEARCH

Effect of spray-drying parameters on the solubility and the bulk density of camel milk powder: A response surface methodology approach

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Response surface methodology coupled with a Box–Behnken experimental design was used to investigate the effect of the air inlet drying temperature, the feed rate, and the fat content on the solubility and the bulk density of spray-dried camel and cow milk powders. The response surface methodology analysis highlighted that milk fat content and feed rate were the most effective parameters affecting the solubility and the bulk density of cow and camel milk powders. Importantly, there was no significant interaction between the studied drying parameters and camel milk powder solubility or bulk density. Overall, camel milk powder exhibited a comparable solubility to that of cow milk powder with a higher bulk density.

Keywords Response surface methodology, Spray-drying, Camel milk powder, Solubility, Bulk density.

INTRODUCTION

Spray-drying is one of the most commonly used techniques to produce milk powder (Schuck *et al.* 2012). In this process, water is quickly evaporated from small milk droplets exposed to hot and dry air. Such drying conditions enable the production of milk powder with acceptable nutritional and functional properties without altering the protein quality. Moreover, converting milk into powder prolongs its shelf life and facilitates its handling (Sharma *et al.* 2012). However, these advantages appear to be dependent on some spray-drying parameters (e.g. inlet and outlet drying temperature, dry air flow rate, product composition and feed rate) (Keshani *et al.* 2015). In fact, each drying parameter affects the physicochemical quality of the milk powder (e.g. solubility, bulk and tapped density, water content and activity, size distribution) and its techno-functional properties (e.g. emulsifying, foaming) (Sharma *et al.* 2012).

The effect of spray-drying parameters on cow milk powder characteristics (e.g. the solubility and the bulk density) has been extensively studied (Birchal *et al.* 2005; Sharma *et al.* 2012; Wu *et al.* 2014). Indeed, it is important to produce soluble milk powder without an excessive loss of nutritional value. The solubility is one of the determining parameters of a powder's hydration ability. It reflects the amount of insoluble material development during dehydration (Schuck *et al.* 2012). It is also necessary to control the bulk density of the produced powder which is an important indicator of the economic cost when converting milk into powder (Sharma *et al.* 2012).

Several studies have reported that the inlet drying temperature affected the particle size and morphology (Fang *et al.* 2012). In fact, it was observed that at lower inlet air-drying temperatures, the dried particles appeared spherical with a collapsed structure. Milk powders with this particle shape present a higher bulk density (Fang and Bhandari 2012). Moreover, in exceeding an inlet drying temperature of 140 °C, milk powder exhibited a poor solubility (Rogers *et al.* 2012). Such observations were attributed to the increase of the hydrophobic interaction between caseins (Havea 2006). Some other research

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studies reported that higher milk fat content tends to decrease the hydration properties of milk powder (e.g. wettability and dispersibility). This was linked to the lower dispersion of fats in water (i.e. higher hydrophobicity) (Wu *et al.* 2014). Likewise, the presence of milk fat decreased the bulk density and the flowability of cow milk powder (Kim *et al.* 2005).

It was shown that camel and cow milk presented some physicochemical differences. Indeed, camel milk presents larger casein micelles and smaller fat globules (Farah and Rüegg 1989; Attia *et al.* 2000). It also has higher β-casein and lower κ-casein content. The soluble fraction of camel milk lacks β-lactoglobulin (Omar *et al.* 2016). Some researchers have investigated the ability of camel milk to be converted into powder through spray-drying (Sulieman *et al.* 2014; Habtegebriel *et al.* 2018). Habtegebriel *et al.* (2018) stated that while varying the level of total solids of the milk (40, 24 and 8.2 g/L), increasing the fat content and the inlet drying temperature has led to the decrease of the bulk density for both cow and camel milk powder. However, a wide variation in total solids content could overlay the effect of milk fat content and inlet drying temperature on the powder's bulk density. In addition, these authors did not consider the effect of feed rate variation in their study. Thus, the purpose of the present study is to investigate the effect of the inlet drying temperature (160, 180, and 200 °C), the feed rate (0.2, 0.6 and 1 L/h), and the milk fat content (1, 14 and 27 g/L for camel milk and 1, 20 and 40 g/L for cow milk) on the solubility and bulk density of camel and cow milk powders with a steady milk solids content.

MATERIALS AND METHODS

Milk samples

Camel (*Camelus dromedarius*) and cow (*Bos taurus*) milk were freshly collected from 9 to 12 milking females (2–10 months in lactation stage) located on Tunisian extensive breeding dairy farms (Gabes and Sfax governorates, respectively). The milk was transported to the laboratory (Valuation, Security and Food Analysis Laboratory, National Engineering School of Sfax, Tunisia) at 4 °C within 2 h of milking. Both types of milk were stabilised against microorganism development by the addition of 0.02% (w/v) of sodium azide. The camel and cow milks composition (Table 1) was determined according to the Official Methods of Analysis (AOAC International 2000). The lactose content of the milk was determined by subtracting the total solid content from the other milk compounds.

Production of milk powder

Experimental design

The Box–Behnken experimental design (three factors with three levels) was used to generate 16 experiments including four centre points (Table 3). The studied variables (Table 2) were the inlet drying temperature (160, 180 and 200 °C), the feed rate (0.2, 0.6 and 1.0 L/h), and the milk fat content (0%, 50% and 100% of total milk fat content). The solubility and the bulk density of the produced powder were immediately evaluated. The Design expert software (version 7.0.0; Stat Ease, Stat-Ease Inc., Minneapolis, MN, USA) was used to evaluate the influence of inlet drying temperature (X_1), milk feed rate (X_2) and milk fat content (X_3) on the solubility and the bulk density of camel and cow milk powder. The statistical significance of the model equation was performed at a 95% confidence level according to the *f*-test and *P*-value. The mathematical model equation is:

$$Y = b_0 \sum_{n=1}^{3} b_n X_n + \sum_{n=1}^{3} b_{nn} X_n^2 + \sum_{n \neq m=1}^{3} b_{nm} X_n X_m \qquad (1)$$

where Y is the response, b_0 is the model constant, and b_n, b_{nn}, b_{nm} are the model coefficients. X represents the studied factors with: (i) linear terms: X_n, (ii) their interactions: $X_n X_m$, and (iii) their quadratic term: X_n^2. The model coefficients could be presented either as coded or experimental values. The coded coefficients are directly linked to the changes in the response. Indeed, they describe the extent of the factors' effects on the studied characteristics (Stat-Ease 2005).

Thereafter, the desirability function was used to optimise the drying conditions. This method enables the research of optimal drying conditions based on the desired goals for each studied response. In this study, the three factors were kept within the studied range, while the solubility and bulk density of both types of milk powder were maximised. Then, the composition of optimised camel and cow milk powder was estimated according to Schuck *et al.* (2012). The powder's carbohydrate content was estimated by subtracting the mean total solid from the sum of all mean compounds.

Spray-drying conditions

The camel and cow milk samples were spray-dried using a Bücchi mini lab scale spray-dryer B-290 (Büchi Labortechnik AG, Flawil, Switzerland), following the suggested drying conditions in the Box–Behnken experimental design (Table 3). Camel and cow milks with different fat levels was obtained following optimised skimming conditions to reach the fat percentage given by the experimental design. Skimmed milks with 1 g/L of fat (which correspond to 0% of total milk fat, Table 2) were obtained after one and three successive skimming operations (2000g, 10 min at 5 °C) for cow and camel milks, respectively. In addition, half-skimmed samples (which correspond to 50% of total milk fat, Table 2) from camel milk with 14 g/L of fat content (600g, 5 min at 4 °C) and cow milk with 21 g/L of fat content (400g, 5 min at 4 °C) were also produced and spray-dried.

During all experiments, the absolute humidity level of the air was equal to 5 g of water per kg of dry air. The water activity of all the powder produced was immediately

Table 1 Physicochemical characteristics of cow and camel milk.

	pH*	a_w*	Solid matter	Fat	Protein	Lactose	Ash
Cow milk (%)	6.81	0.96	12.4 ± 0.5[a]	4.0 ± 0.1[a]	3.4 ± 0.5[a]	4.7 ± 0.2[a]	0.8 ± 0.1[a]
Camel milk (%)	6.75	0.96	11.8 ± 0.2[a]	2.7 ± 0.5[b]	3.2 ± 0.2[a]	5.0 ± 0.1[a]	1.1 ± 0.1[b]

%, g/100 g (dry matter); a_w, water activity.
*Measurements were carried out at 25 °C.
Same letter in the same column represent the statistical data significance ($P > 0.05$).

Table 2 The studied factors and their levels.

Factors	Factor levels		
Coded value	−1	0	+1
Experimental value			
X_1: Inlet drying temperature (°C)	160	180	200
X_2: Feed rate (L/h)	0.2	0.6	1
Milk fat content			
Cow milk (g/L)	<1	21 ± 0.1	40 ± 0.1
Camel milk (g/L)	<1	14 ± 0.1	27 ± 0.1
X_3: Normalised milk fat content (Values are expressed in % of total milk fat)	0	50	100

analysed using an a_w-meter (Aw-sprint; TH, 500; Novasina, Pfäffikon, Switzerland) at 25 °C.

The size distribution of camel and cow milk powder was determined using a light laser scattering Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK), equipped with a dry powder feeder (Scirocco 2000; Malvern Instruments, Worchestershire, UK). The feeder was operated at a vibration rate of 40% and a dispersive air pressure of four bars. As recommended by Nikolova *et al.* (2014), the d_{50} diameter was chosen as a size distribution indicator.

Physicochemical properties

Powder solubility test

The amount of insoluble material was used as a solubility indicator. As described by Anema *et al.* (2006), about 1 g of the produced camel and cow milk powder was dissolved in 20 mL of ultrapure water. The obtained mixture was vigorously stirred (500 rpm) for 30 min at 30 °C to ensure a complete dispersion of the powder. Then, the reconstituted milk was divided into four aliquots of 5 mL, which were centrifuged at 700 g for 10 min. The total solids of each aliquot and the corresponding supernatant were then estimated as described by Schuck *et al.* (2012). The solubility value was evaluated as follows:

$$\text{Solubility}\ (\%) = \frac{\text{TS aliquot} - \text{TS supernatant}}{\text{TS aliquot}} \times 100 \quad (2)$$

Powder loose bulk density

The loose bulk density of camel and cow milk powders was determined using a tarred graduated cylinder (length 145 mm; diameter 5 mm). The volume of the seeded powder was recorded (without tapping) and was integrated into the following formula:

$$\text{Bulk density}\ \left(\text{kg/m}^3\right) = \frac{\text{powder weight (kg)}}{\text{readable volume}\ (\text{m}^3)} \quad (3)$$

Statistical analysis

The composition of the powder and milk was performed in triplicate and was presented as mean and standard deviation. The statistical differences were examined using SPSS 19 software (IBM SPSS statistics, Version 19, New York, USA) following Student's *t*-test with a confidence level of 95%.

RESULTS AND DISCUSSIONS

Milk composition

The physicochemical composition of whole camel and cow milks is shown in Table 1. Camel milk presented a slightly lower pH value (6.75) than cow milk (pH = 6.81) and similar water activity. Results of this study indicated that camel and cow milks had similar solid matter, protein and lactose content ($P > 0.05$, Table 1). However, camel milk contained significantly higher ash quantity of 1.1 ± 0.1 g/100 g against 0.8 ± 0.1 g/100 g in cow milk ($P < 0.05$, Table 1). Furthermore, the analysis of the composition of camel milk highlighted significantly lower fat content (2.7 ± 0.5 g/100 g) than cow milk (4.0 ± 0.1 g/100 g). These differences could be related to the specificities of the species themselves, the feeding and veterinary practices.

Model fitting and validation

The generated response surface methodology (RSM)–ANOVA reports for camel and cow milk powders characteristics are summarised in Tables 4 and 5. The authenticity of

Table 3 The Box–Behnken experimental design used to study the characteristics of camel and cow milk powder.

	Factors						*Characteristics*			
	Coded values			*Experimental values*			*Solubility (%)*		*Loose bulk density (kg/m^3)*	
Run	*Inlet drying temperature*	*Feed rate*	*Normalised fat content*	*Inlet drying temperature (°C)*	*Feed rate (L/h)*	*Normalised fat content (%)*	*Cow*	*Camel*	*Cow*	*Camel*
1	−1	−1	0	160	0.2	50	81.0	81.8	143	156
2	1	−1	0	200	0.2	50	84.3	82.9	144	152
3	−1	1	0	160	1	50	73.8	75.8	173	192
4	1	1	0	200	1	50	78.6	81.3	156	172
5	−1	0	−1	160	0.6	0	93.3	91.8	173	210
6	1	0	−1	200	0.6	0	92.3	93.3	161	215
7	−1	0	1	160	0.6	100	74.2	77.3	175	201
8	1	0	1	200	0.6	100	75.1	78.6	139	192
9	0	−1	−1	180	0.2	0	98.7	96.2	161	207
10	0	1	−1	180	1	0	82.1	83.7	152	220
11	0	−1	1	180	0.2	100	69.0	78.6	125	185
12	0	1	1	180	1	100	68.8	67.3	192	217
13	0	0	0	180	0.6	50	86.1	82.4	164	225
14	0	0	0	180	0.6	50	88.9	84.6	167	200
15	0	0	0	180	0.6	50	86.0	87.4	172	210
16	0	0	0	180	0.6	50	80.1	82.2	170	212

the estimated model equations (Table 4) was checked by taking into consideration several parameters (i.e. the lack of fit, the regression coefficient (R^2), the adjusted R^2 and the coefficient of variation: C.V). In fact, the R^2 and the adjusted R^2 measure of the amount of variation around the mean are explained by the model. The difference is that the adjusted R^2 takes into consideration the number of significant terms in the model. As the number of insignificant terms in the model increases, the adjusted R^2 decreases (Stat-Ease 2005). The C.V represents the ratio between the SD and the mean which shows the extent of the data variability (Stat-Ease 2005). A C.V below 10 indicated a good model reproducibility (Firatligil-Durmus and Evranuz 2010).

The results showed that the quadratic models were significant for all analysed milk powder characteristics ($P < 0.05$, Table 4). Analysis of the obtained data for solubility showed that the estimated regression coefficient R^2 was equal to 0.94 and 0.92 for cow and camel milk powders, respectively. Likewise, the adjusted R^2 values were 0.87 and 0.81 for cow and camel milk powders, respectively. Although the R^2 and the adjusted R^2 are relatively low, the C.V values (3.76 and 3.66 for cow and camel milk powders, respectively) suggested a great precision and a high reliability of the realised experiments. By the same token, the findings showed that the models of cow and camel milk powders bulk density had an R^2 of 0.93 and 0.94, respectively (Table 4). In addition, the recorded adjusted R^2 values were 0.83 and 0.86 for cow and camel milk powders, respectively (Table 4). Furthermore, the C.V values were equal to 4.17 and 4.06 (<10) for cow and camel milk powders, respectively.

For all the analysed models, the lack of fit for solubility and bulk density were not significant ($P > 0.05$, data not shown). In fact, the lack of fit measures the overall variation of the experimental data around the predicted model. The insignificance of the lack of fit, the reasonable R^2 and the adjusted R^2 values, and the relatively lower C.V, suggest that all the obtained quadratic models are valid for predicting and evaluating the studied factors.

Response surface methodology analysis

Powder solubility

The production of milk powder with high solubility is a key condition for its future uses. Indeed, the solubility is one of the most important steps in the milk powder reconstitution process (Freudig *et al.* 1999). Figures 1 (a,b) show the three-dimensional plots of the effect of milk fat content and milk feed rate on camel and cow milk powders solubility, respectively. The findings highlighted that both cow and camel milk powders solubility was negatively affected by the feed rate and fat content ($P < 0.05$, Table 5). However,

Table 4 The obtained models for the studied physicochemical properties of camel and cow milk powder.

Powder characteristic	*Models**	R^2	*Adjusted* R^2	*C.V (%)*
Solubility (%)				
Cow milk	$= -23.5 + 9.2X_2 - 0.38X_3 + 0.2X_2X_3 - 31X_2^2$	0.94	0.87	3.76
Camel milk	$= +98.87 - 7.2X_2 - 0.20X_3 - 23.4X_2^2$	0.92	0.81	3.66
Loose bulk density (kg/m^3)				
Cow milk	$= -280.1 + 4.62X_1 - 155.31X_2 + 0.95X_2X_3 - 58.6X_2^2$	0.93	0.83	4.17
Camel milk	$= -1760.3 + 263.4X_2 - 0.30X_3 - 0.06X_1^2 - 132.0X_2^2 + 0.006X_3^2$	0.94	0.86	4.06

X_1, Inlet drying temperature; X_2, Milk feed rate; X_3, Milk fat content; C.V, Coefficient of variation.
*Each model equation is presented using the significant experimental values ($P < 0.05$).

Table 5 Significance of the studied factors.

	Solubility (%)		*Loose bulk density (kg/m^3)*	
Equation terms	*Cow*	*Camel*	*Cow*	*Camel*
Linear terms				
X_1	NS	NS	–	NS
X_2	–	–	+	+
X_3	–	–	NS	–
Interactions				
X_1X_2	NS	NS	NS	NS
X_1X_3	NS	NS	NS	NS
X_2X_3	+	NS	+	NS
Quadratic terms				
X_1^2	NS	NS	NS	–
X_2^2	–	–	–	–
X_3^2	NS	NS	NS	+

X_1, Inlet drying temperature; X_2, Milk feed rate; X_3, Milk fat content; +, positive effect ($P < 0.05$); –, negative effect ($P < 0.05$); NS, Not significant.

it was observed that the inlet drying temperature did not influence the solubility of both powder ($P > 0.05$, Table 5). Besides, these results underlined that a positive interaction between fat content and feed rate had improved the solubility of cow milk powder ($P < 0.05$, Table 5). Nevertheless, there was no interaction between the studied factors and camel milk powder solubility ($P > 0.05$, Table 5). Furthermore, only the quadratic term of feed rate influenced the solubility of both types of milk powder ($P < 0.05$, Table 5).

For a better understanding of the observed effect on camel and cow milk powder solubility, the generated perturbation plots (Figure 3a,b) were analysed. Indeed, the perturbation plots allowed the analysis of each individual factor effect at a particular point in the design space. Otherwise, they can be used to find the most influencing factor on the response (Stat-Ease 2005). In fact, while increasing the fat level from 0% to 100%, a solubility loss of 21% (from 95% to 75%, Figure 3a) and 17% (from 93% to 77%, Figure 3b) was observed for cow and camel milk powders, respectively. The perturbation plots showed a significant decrease (from approximately 84% to 76%) for the solubility of both types of milk powder (i.e. 10% of solubility loss) with an increase of the milk feed rate, especially above 0.6 L/h. These results indicated that the milk fat content could be considered as the main influencing factor on the solubility of both types of milk powder.

Powder loose bulk density

Powder density is associated with the economic challenge in dairy industries (e.g. packaging, transport and storage coast). The RSM results for cow and camel milk powders showed that bulk density was positively affected by the feed rate ($P < 0.05$, Table 5). However, some specificities were highlighted for each milk powders, regarding the variation of milk fat content and the inlet drying temperature (Table 5).

The significant influencing factors on camel and cow milk powders bulk density were converted into three-dimensional plots (Figures 2a,b, respectively). Only the bulk density of camel milk powder decreased with the increase of milk fat content ($P < 0.05$, Table 5, Figure 2a). In addition, contrary to the results for cow milk powder, the inlet drying temperature did not influence the bulk density of camel milk powder ($P > 0.05$, Table 5). The quadratic terms of the studied parameters significantly influenced the bulk density of camel milk powder ($P < 0.05$, Table 5). This indicated that larger ranges of the studied factors would modify the loose bulk density of camel milk powder. Similarly, as observed for camel milk powder solubility, there was no significant interaction between the studied factors that influence the loose bulk density ($P > 0.05$, Table 5). In addition, the RSM analysis pointed out the same interaction between milk feed rate and milk fat content, which positively raises the bulk density of the cow milk powder ($P < 0.05$, Table 5).

Furthermore, the perturbation plots for the loose bulk density of both types of milk powder were studied (Figures 3c, d). It was observed that raising the feed rate from 0.2 to 1 L/h resulted in an increase of 14% in the bulk density of both types of milk powder. Besides, increasing the milk fat

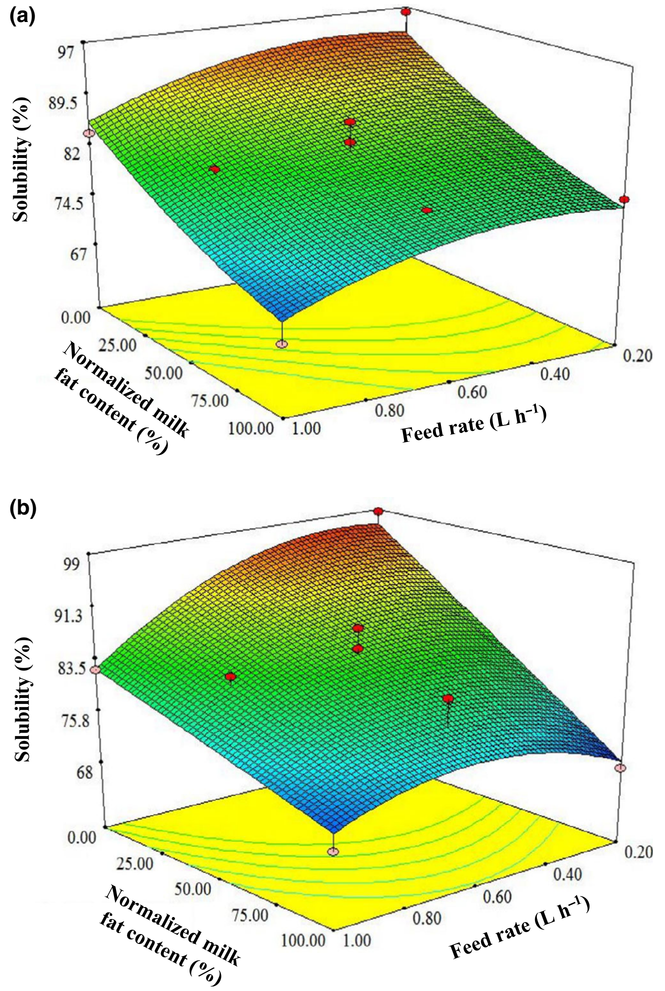

Figure 1 3D plots of significant factors on camel (a) and cow milk powder (b) solubility at inlet drying temperature of 180 °C. [Colour figure can be viewed at wileyonlinelibrary.com]

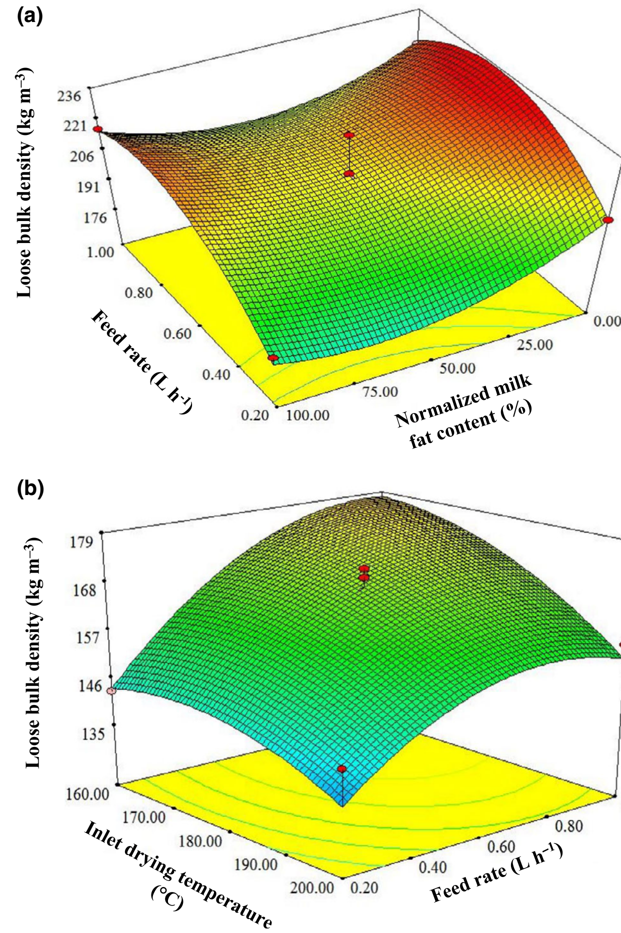

Figure 2 3D plots of significant factors on camel milk powder (a) at an inlet drying temperature of 180 °C and cow milk powder (b) bulk density at a milk fat content of 50%. [Colour figure can be viewed at wileyonlinelibrary.com]

content led to the decrease of the bulk density of camel milk powder by 6% (Figure 3c). A loss of 10% of cow milk powder bulk density was observed as a result of the variation of the inlet drying temperature (Figure 3d).

Interpretation of the individual effect

Inlet drying temperature

The inlet drying temperature is a key parameter that determines the drying kinetic and the first features of dried particles' morphology (Fang *et al.* 2012). Previous studies on the effect of inlet drying temperature reported that milk powder with constant total milk solids showed a poor solubility at an inlet drying temperature above 140 °C (Rogers *et al.* 2012; Reddy *et al.* 2014). In this work, the inlet drying temperature ranged from 160 to 200 °C (Table 2) and it did not influence the solubility of camel or cow milk powder (Table 5). It seems that the majority of the insoluble material is formed below 160 °C. Anema *et al.* (2006) reported that the insoluble aggregates are composed of caseins, which are interconnected by hydrophobic interactions. In this study, it was observed that for cow and camel milk powders, the maximal solubility values were equal to 98.7% and 96.2%, respectively. These trends suggested that camel milk powder is more suitable for the development of insoluble material through hydrophobic interactions.

Besides, at a high drying temperature, a hard crust at the particle surface is rapidly formed (Nijdam and Langrish 2006). This layer constitutes a vapour-impermeable film and allows the formation of vapour bubbles inside the particles until disruption. Powder particles become more voluminous with a porous structure, leading to the decrease of the loose bulk density (Reddy *et al.* 2014). In this study, at a high drying temperature, the analysis of the d_{50} (size indicator) showed that cow milk powder presented higher values (up to 13 μm) than did camel milk powder (up to 11 μm). This could explain the significant effect of inlet drying

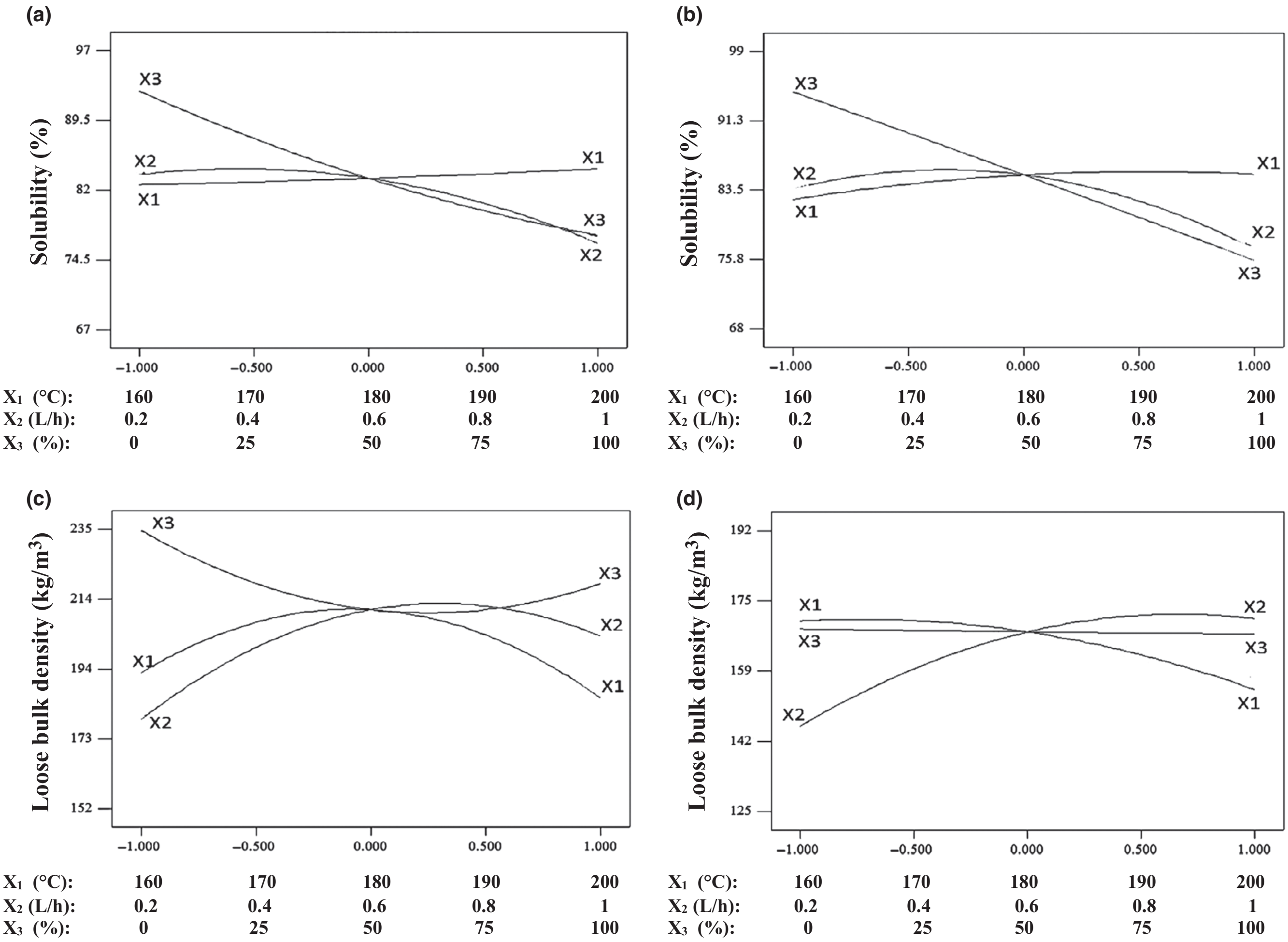

Figure 3 Perturbation plots of camel (a,c) and cow (b,d) milk powder solubility and loose bulk density. X_1, inlet drying temperature; X_2, milk feed rate and; X_3, milk fat content.

temperature on the loose bulk density of cow milk powder (Table 5). However, the effect of the inlet drying temperature on the bulk density of camel milk powder particles was irrelevant, suggesting that despite the formation of the hard crust at the surface, the extent of the disruption is not the same as could be observed for cow milk powder.

Milk feed rate

The effect of the feed rate is directly related to the behaviour of milk droplets during the different dehydration steps of the spray-drying. In fact, as a direct consequence of increasing the milk feed rate, there was a rise in residual water content (i.e. lower drying kinetic) (Schuck *et al.* 2008). At a higher feed rate (up to 1 L/h) the water activity of camel milk powder ranged from 0.334 to 0.452. However, it varied from 0.345 to 0.523 for cow milk powder. In this range of water activity, the rate of deteriorative reactions (e.g. nonenzymatic hydrolysis and browning) could be increased, including the development of insoluble material through hydrophobic interactions (Havea 2006).

On the other side, the increase of the feed rate induces the expansion of the mean diameter of milk droplets during drying (Birchal *et al.* 2005). Therefore, the size distribution of milk powder particles increased. These particles become heavier because of the high residual water content, inducing an increase of the loose bulk density (Chu *et al.* 2006). The above observations are a good fit for the recorded positive effect of feed rate on the loose bulk density of both types of milk powder.

Milk fat content

Milk could be assimilated to an emulsion in which the fat globules are dispersed in a protein–water matrix. Actually, fats play a major role in the structuring of dried milk

Table 6 Characterisation of the optimal cow and camel milk powder.

		Physicochemical composition (g/100 g)*					Solubility (%)		Bulk density (kg/m)	
	a_w	Solid matter	Fat	Protein	Lactose	Ash	PR	MR	PR	MR
OCMP	0.198	96.8 ± 0.2[a]	0.6 ± 0.1[a]	33.5 ± 0.1[a]	53	9.1 ± 0.8[a]	96	94.8 ± 1.1[a]	170	196 ± 0.1[a]
ODMP	0.202	96.9 ± 0.3[a]	0.5 ± 0.1[a]	30.4 ± 0.2[b]	55.5	10.5 ± 0.9[a]	93.5	93.5 ± 0.9[a]	230	235 ± 0.1[b]

MR, Measured value; OCMP, Optimal cow milk powder; ODMP, Optimal camel milk powder; PR, Predicted value.
*Dry matter basis.
Same letter in the same column represent the statistical data significance ($P > 0.05$).

particles and in their future functionalities. Compared with cow milk, camel milk is composed of smaller fat globules (Attia *et al.* 2000). Thus, it was expected that different behaviour of camel milk fats would be observed during spray-drying. Studies of the structure of whole cow milk powder reported that during spray-drying, fats are exposed to the surface and form a hydrophobic layer around the dried particles (Vignolles *et al.* 2009). This layer leads to the decrease of cow milk powder's solubility, not only by decreasing the powder's wettability (Wu *et al.* 2014), but also by promoting the hydrophobic interactions between proteins. This trend could explain the observed effect of milk fat on camel and cow milk powder solubility (Table 5). In other studies, it was highlighted that the fat globules seemed to have a uniform distribution inside homogenised (reduced fat globule size) milk powder particles. In fact, the confocal microscopy examination of the homogenised milk powder showed that the smallest fat globules preserved their initial size inside powder particles and did not coalesce during spray-drying (Vignolles *et al.* 2009). Thus, the exposure of these fat globules to the surface could be limited. According to Attia *et al.* (2000), camel milk fat globules are naturally smaller than those of cow milk. Therefore, it can be deduced that, due to their small size, the majority of camel milk fat globules are uniformly dispatched and encapsulated in the core of dried particles. This could explain the negative effect of the milk fat content on the loose bulk density of camel milk powder.

It is highly interesting to note that milk fat content is involved in a positive interaction with the feed rate. This interaction significantly increased the solubility and the loose bulk density of the cow milk powder. This observation could be explained by the overexposure of fat at the droplet surface of cow milk when dried at a high feed rate. As a result, the fat layer became thicker and constitutes a barrier to water evaporation (i.e. high residual water), leading to a high loose bulk density. Besides, fats could limit the hydrophobic interactions between the proteins by increasing the amount of solvent water. Therefore, the amount of insoluble material is reduced, leading to an improved solubility for the cow milk powder.

Optimised camel milk powder

Optimisation of drying conditions

The desirability approach was used to optimise the spray-drying conditions and to estimate the predicted responses. In this study, a high solubility and a high loose bulk density for both types of milk powder were targeted. Through the RSM optimisation process, a desirability of 0.87 was obtained. For both types of milk powder, the estimated operating parameters were: inlet drying temperature, 180 °C; milk feed rate, 0.6 L/h; milk fat content, 0% (correspond to 1 g/l).

Physicochemical characterisation

The characteristics of the optimal produced powder are summarised in Table 6. Under optimal drying conditions, cow and camel milk powders showed a similar total solid and ash content ($P > 0.05$, Table 6). However, camel milk powder presented a significant lower protein level and a higher lactose content ($P < 0.05$, Table 6). The predicted and experimental values of the powder solubility were concordant ($P > 0.05$, Table 6). There was no statistical difference between the solubility of the types of milk powder (93.5 ± 0.9% and 94.8 ± 1.1% for camel and cow milk powder solubility, respectively, $P < 0.05$, Table 6). The measured loose bulk density value was in agreement with the predicted value for both types of powder ($P > 0.05$, Table 6). In addition, for the same solid content, we found that camel milk powder had a higher loose bulk density than cow milk powder ($P < 0.05$, Table 6).

CONCLUSION

In this work, the effect of the air inlet drying temperature, the milk feed rate, and the milk fat content on the solubility and the loose bulk density of camel and cow milk powder were investigated using the Box–Behncken experimental design and RSM. Results of this study indicated that the solubility of camel and cow milk powders was affected primarily by the milk fat content. Fundamental differences were found regarding the analysis of the loose bulk density of both types of milk powder. The RSM analysis highlighted that increasing the milk fat content only induced a decrease of the loose bulk density of camel milk powder. However, the inlet drying temperature only affected the loose bulk density of cow milk powder. These divergences were linked to the physicochemical differences between camel and cow milk, especially the fat globule characteristics. Finally, under optimised drying conditions, there was no statistical difference between the solubility of the types of milk powder. However, it was found that camel milk powder had a significant higher loose bulk density than that of cow milk powder.

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