



**HAL**  
open science

## Impact of spray-drying conditions on flow properties of skim dromedary and cow's milk powders using the FT4 powder rheometer

Imène Felfoul, Jennifer Burgain, Carole Perroud, Claire Gaiani, Joël Scher, Hamadi Attia, Jérémy Petit

### ► To cite this version:

Imène Felfoul, Jennifer Burgain, Carole Perroud, Claire Gaiani, Joël Scher, et al.. Impact of spray-drying conditions on flow properties of skim dromedary and cow's milk powders using the FT4 powder rheometer. *Journal of Food Processing and Preservation*, 2021, 45 (6), 10.1111/jfpp.15566 . hal-03330387

**HAL Id: hal-03330387**

**<https://hal.univ-lorraine.fr/hal-03330387>**

Submitted on 31 Aug 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.

# Impact of spray-drying conditions on flow properties of skim dromedary and cow's milk powders using the FT4 powder rheometer

Imène Felfoul, Jennifer Burgain, Carole Perroud, Claire Gaiani, Joël Scher, Hamadi Attia, Jérémy Petit

► **To cite this version:**

Imène Felfoul, Jennifer Burgain, Carole Perroud, Claire Gaiani, Joël Scher, et al.. Impact of spray-drying conditions on flow properties of skim dromedary and cow's milk powders using the FT4 powder rheometer. *Journal of Food Processing and Preservation*, Wiley, 2021, 45 (6), 10.1111/jfpp.15566 . hal-03330387

**HAL Id: hal-03330387**

**<https://hal.univ-lorraine.fr/hal-03330387>**

Submitted on 31 Aug 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.

**Impact of spray-drying conditions on flow properties of skim dromedary and cow's milk powders using the FT4 powder rheometer**

Journal:	<i>Journal of Food Processing and Preservation</i>
Manuscript ID	JFPP-09-20-2207.R1
Manuscript Type:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Felfoul, Imène; National Engineering School of Sfax Burgain, Jennifer ; Universite de Lorraine, Physicochimie et génie des procédés alimentaire Perroud, Carole; Universite de Lorraine, LIBio GAIANI, Claire; Université de Lorraine, LIBio (Laboratoire d'Ingénierie des biomolécules Scher, Joël; Universite de Lorraine, LIBio attia, hamadi; Ecole Nationale d'Ingenieurs de Sfax Petit, Jeremy; University of Lorraine, Biomolecular Research
Keywords:	spray-drying, flowability, dromedary milk powder, basic flowability energy, specific energy

1  
2  
3 **1 Impact of spray-drying conditions on flow properties of skim dromedary**  
4  
5  
6 **2 and cow's milk powders using the FT4 powder rheometer**  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

3  
4 **Imène FELFOUL<sup>a\*</sup>, Jennifer BURGAIN<sup>b</sup>, Carole PERROUD<sup>b</sup>, Claire GAIANI<sup>b</sup>,**  
5 **Joël SCHER<sup>b</sup>, Hamadi ATTIA<sup>a</sup>, Jérémy PETIT<sup>b</sup>**

6 \*Corresponding author. Tel.: +216 74 675 761

7 E-mail address: [imenef@gmail.com](mailto:imenef@gmail.com) / [imen.falfoul@isbs.usf.tn](mailto:imen.falfoul@isbs.usf.tn)

8  
9 <sup>a</sup> Université de Sfax, Laboratoire Analyses, Valorisation et Sécurité des Aliments (LAVASA),  
10 Ecole Nationale d'Ingénieurs de Sfax, Route de Soukra, 3038 Sfax, Tunisia

11 <sup>b</sup> Université de Lorraine, LIBio (Laboratoire d'Ingénierie des Biomolécules), F-54000 Nancy,  
12 France.

### 13 **ABSTRACT**

14 Two sets of spray-drying conditions were applied on skim dromedary and cow's milks  
15 to determine the effect of air outlet temperature (75 and 85 °C) and milk type on proximate  
16 composition, particle size distribution, and flow properties of spray-dried powders. The particle  
17 size distribution was more influenced by the chemical composition than the spray-drying  
18 conditions. The air outlet temperature impacted on dromedary milk powder flowability, as the  
19 basic flowability energy was significantly increased from 620 to 1018 mJ when the outlet air  
20 temperature was increased from 75 to 85 °C, respectively. Specific energy, associated with the  
21 flow performance of a powder in a low stress environment, were significantly higher for  
22 dromedary milk powder at the higher air outlet temperature. However, spray-drying conditions  
23 had no significant effect on specific energy values of cow's milk powder. Dromedary milk  
24 powders had better flow behavior than cow's milk powders. Shear tests confirmed that powders  
25 spray-dried at 75 °C had better flowability than powders spray-dried at 85 °C.

### 26 **NOVELTY IMPACT STATEMENT**

27 Powdering is particularly interesting for dromedary milk industrialization, as a way to  
28 overcome problems related to production seasonality and commercialization in low production  
29 regions. Using a lower air outlet temperature (75 °C) led to better flowability and lower  
30 compressibility. Shear tests showed that cow's milk powders were more cohesive than  
31 dromedary milk powders.

32 **Keywords:** spray drying; flowability; dromedary milk powder; basic flowability energy;  
33 specific energy; shear test.

## 1. INTRODUCTION

Milk transformation into a powdered product by means of a drying process is widely used in the dairy industry (Hammes, Englert, Noreña, & Cardozo, 2015). Milk powder can be preserved for longer times and its production reduces the cost of certain operations, such as packing, storage, and transportation (Kitamura, Itoh, & Echizen, 2009). Powdering processes allow the almost complete preservation of nutrients (Gaiani et al., 2010). In the case of dromedary milk, powdering is particularly interesting for product industrialization, as a way to overcome problems related to production seasonality and commercialization in low production regions. Indeed, it is possible to store powdered milk in areas and periods of high production, in order to fulfill the demand where and when dromedary milk is not produced enough.

The drying step determines the quality of resulting powder; the choice of drying method and conditions is dictated by the nature of the material to be dried, the desired powder functionalities, and economic factors (Jinapong, Suphantharika, & Jamnong, 2008; Esquivel & Jiménez, 2012). Spray-drying is the most commonly used technique for industrial production of milk powder, because it generates a product of good quality with better organoleptic and nutritional features than drum-drying, while being faster and cheaper than freeze-drying (Ceballos, Giraldo, & Orrego, 2012; Reddy et al., 2014).

To the best of our knowledge, only a few studies in the literature have been dedicated to spray-dried dromedary milk powder and they were restricted to the determination of the influence of the drying process on the nutritional, physicochemical, and organoleptic properties of powders, as well as their storage stability. For instance, Sulieman, Elamin, Elkhalifa, and Laleye (2014) reported that the physicochemical and functional properties of spray-dried dromedary milk powder (water activity, powder color, solubility, flowability) were greatly affected by the velocity difference (both in terms of intensity and direction) between feed and air and they described thermal properties of freeze-dried whole and skim dromedary milks on

1  
2  
3 59 the basis of glass transition and melting temperatures of their major components (lipids, caseins,  
4  
5 60 whey proteins, and lactose). Al-Juboori, Mohammed, Rashid, Kurian, and El Refaey (2013)  
6  
7 61 revealed the dependence of physicochemical properties (water activity, glass transition  
8  
9 62 temperature, bulk density, free fat content, and whey protein nitrogen index) of spray-dried  
10  
11 63 dromedary milk powders on fat content of feeding concentrate and spray-drying temperature.  
12  
13 64 Zouari et al. (2019) investigated the effect of spray-drying parameters on the production of  
14  
15 65 dromedary milk powder (water activity, glass transition temperature, bulk density, and free fat  
16  
17 66 content). Ho et al. (2019) evaluated the stability of spray-dried dromedary milk powder and  
18  
19 67 denoted modifications of several physicochemical properties upon accelerated aging. To the  
20  
21 68 authors' knowledge, there has been no study on the effect of spray-drying conditions on flow  
22  
23 69 properties of dromedary skim milk powder. Good powder flow properties enable high  
24  
25 70 production efficiency as well as improved powder product quality (Fitzpatrick et al., 2007;  
26  
27 71 Krantz, Zhang, & Zhu, 2009). Indeed, in manufacturing processes involving powders as  
28  
29 72 ingredients or products, many unit operations, such as transfer from a silo or hopper,  
30  
31 73 fluidization, pneumatic transportation, and mixing, require good flow properties of handled  
32  
33 74 powders. Insufficient powder flow may be detrimental for the monitoring of some unit  
34  
35 75 operations, resulting in poor quality of the end product (for instance, cohesive powders  
36  
37 76 generally are more susceptible to agglomerate, resulting in particle sizes higher than  
38  
39 77 specifications) and/or modifications of process conditions (for example, cohesive powders are  
40  
41 78 more hardly fluidized, thus necessitating the use of higher air velocities for fluidization  
42  
43 79 purposes, leading to more intense interparticular and particle-wall shocks that are likely to break  
44  
45 80 particles and affect their size and shape). Moreover, good flow is required in powder mixing  
46  
47 81 processes to ensure even distribution: it is more difficult to form a homogeneous mixture with  
48  
49 82 cohesive powders or agglomerates than with powders composed of non-cohesive individual  
50  
51 83 particles (Krantz, Zhang, & Zhu, 2009). The characterization of powder flowability can be  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 84 achieved with the FT4 powder rheometer (Freeman Technology). Flow properties of various  
4  
5 85 food products have been determined using the FT4 powder rheometer: for instance, powdered  
6  
7 86 dairy products (Lapčik et al., 2015), fermented milk-cereal mixtures (Salameh et al., 2016), and  
8  
9 87 plantain-based formulated powders (Gnagne, Petit, Gaiani, Scher, & Amani, 2017).

10  
11  
12 88 Two sets of spray-drying process conditions were applied on skim dromedary and cow's  
13  
14 89 milks in order to evaluate the impact of drying air temperature and milk type on the flow  
15  
16 90 properties of resulting milk powders. The proximal composition and the particle size  
17  
18 91 distribution were also evaluated in order to better understand the links between physicochemical  
19  
20 92 properties and flowability of studied powders.

## 23 24 25 93 **2. MATERIAL AND METHODS**

### 26 27 94 **2.1. Dromedary and cow's milk samples**

28  
29 95 Dromedary (*Camelus dromedarius*) milk was obtained from a local breeding located in  
30  
31 96 the south of Tunisia (Gabès governorate, Tunisia). Dromedary milk was constituted of pooled  
32  
33 97 milk samples assembled from twenty different healthy dromedaries (*Camelus dromedarius*),  
34  
35 98 whose lactation time ranged between 2 and 8 months. Cow's milk, collected from healthy  
36  
37 99 Holstein cows, was provided by a farm located in the north-east of France (experimental domain  
40  
41 100 of La Bouzule, ENSAIA, Laneuvelotte, France). Both milks were collected in sterile milking  
42  
43 101 cans, in which sodium azide was promptly added up to 0.02 % (w/w) to ensure microbiological  
44  
45 102 stability; after that, they were conveyed into a cool box filled with ice to the laboratory and then  
46  
47 103 stored at 4 °C until skimming. Both milks were skimmed at  $3\ 000 \times g$  during 20 min at 4 °C  
48  
49 104 (Gyrozen 1580MGR, Multi-purpose Centrifuge, Daejeon, Korea). Then, both skim milks were  
50  
51 105 stored at -20 °C until use for spray-drying.

### 52 53 54 106 **2.2. Spray-drying of skim dromedary and cow's milks**

55  
56  
57 107 Skim dromedary and cow's milks were sieved at 50 µm mesh size (test sieve, Mesh S-  
58  
59 108 Steel, 200 mm diameter, 50 mm height, Retsch GmbH, Germany) in order to remove the  
60



1  
2  
3 109 potential residual coalesced fat globules. Spray-drying of skim milks was performed in a  
4  
5 110 MicraSpray MS 150 simple effect pilot plant spray-dryer (Anhydro, Soeborg, Denmark)  
6  
7  
8 111 equipped with a bi-fluid nozzle (Fluid Cap 60 100 + Air Cap 120, Spraying System, Wheaton,  
9  
10 112 Illinois, USA). Aspiration rate was set at 70 % for all performed assays. In the drying chamber,  
11  
12 113 the drying air cocurrently flowed with milk droplets sprayed from the bi-fluid nozzle. The  
13  
14 114 spray-dryer was fed at 27 °C with a FAST Load peristaltic pump (VWR, Leuven, Belgium, 48  
15  
16 115 mm internal pipe diameter). Dromedary and cow's milks were first skimmed, then stored at –  
17  
18 116 20 °C. For spray-drying experiments, both skim milks were thawed out at 4 °C overnight. Last,  
19  
20 117 both milks were prewarmed at 27 °C in a water bath to improve spray-drying production  
21  
22 118 efficiency (mainly, pumping of the concentrate through the bi-fluid nozzle).  
23  
24  
25

26 119 The spray-drying conditions such as air inlet and outlet temperatures as well as drying  
27  
28 120 air flow rate suitable for the production of skim milk powder were selected not only based on  
29  
30 121 literature (Schuck, Jeantet, & Dolivet, 2012) and but also after preliminary experimentations in  
31  
32 122 order to obtain skim milk powders suitable for storage, i.e. having a moisture content not  
33  
34 123 exceeding 5 % (w/w) (Schuck, Jeantet, & Dolivet, 2012; Felfoul et al., 2020). Two assays  
35  
36 124 differing in spray-drying conditions were carried out with a view to evaluate the influence of  
37  
38 125 air outlet temperature (Table 1). It is worth noting that C1 and C2 spray-drying conditions  
39  
40 126 differed in outlet air temperature (circa 74.5 and 84.5 °C, respectively) and feed flow-rate (about  
41  
42 127 75 and 67 mL.min<sup>-1</sup>, respectively).  
43  
44  
45

46 128 With this experimental setup, the process parameter having the most influence on  
47  
48 129 powder physicochemical and functional properties should be the air outlet temperature rather  
49  
50 130 than the feed flow-rate. The feed flow rate was a little higher in C1 conditions (Table 1),  
51  
52 131 meaning that liquid velocity at the nozzle outlet was a little higher and resulting in slightly  
53  
54 132 lower air–liquid velocity difference at the nozzle outlet; this should result in slightly larger  
55  
56 133 droplets (Petit et al., 2015; Mandato et al., 2012) and thus slightly larger spray-dried particles  
57  
58  
59  
60

1  
2  
3 134 in C1 conditions. However, the effect of feed flow-rate was likely negligible compared to the  
4  
5 135 one of drying air temperature, because the air–liquid velocity difference at the nozzle outlet was  
6  
7  
8 136 not markedly affected by changing the feed flow-rate, as the air velocity is much greater than  
9  
10 137 the liquid velocity at the outlet of a bi-fluid nozzle (Petit et al., 2015; Mandato et al., 2012).

11  
12 138 The powders were then collected, immediately packed in sealed polyethylene  
13  
14 139 terephthalate bags, and stored at 10 °C until analysis. All analyses were carried out within a  
15  
16 140 week after powder production. Spray-drying yield was calculated as the ratio between the dry  
17  
18 141 mass of powder and the dry mass of feed skim milk.

### 142 **2.3. Proximate composition of skim dromedary and cow's milks and powders**

143 Moisture, protein, and ash contents of skim milks and powders were determined  
144 according to the AOAC standard methods (A.O.A.C., 2016). Moisture content was determined  
145 by mass loss after drying 10 mL milk or 3 g powder in an air oven at 105 °C for 7 h. Ash content  
146 was obtained by mass loss after incinerating 10 mL milk sample or 3 g powder in a furnace at  
147 550 °C during 6 h. Proteic nitrogen content was determined by the Kjeldahl method (Vapodest,  
148 Gerhardt GmbH & Co. KG, Königswinter, Germany) and protein content was deduced from  
149 nitrogen content using a conversion factor of 6.38 (Felfoul et al. 2020).

150 Fat content of milks (using 11 mL milk sample) was determined according to the Gerber  
151 acid-butyrometric method (ISO 11870:2009) using 10 mL of sulfuric acid in order to dissolve  
152 milk proteins. The fat separation was carried out by centrifugation in a butyrometer at 1100  
153 tr/min for 5 min at 65 °C in the presence of 1 mL of isoamyl alcohol. Fat content of powders  
154 was determined using the Folch method (1957) by performing solvent extraction of 2 g powder  
155 using a mix of 2:1 (v/v) chloroform/methanol.

156 Carbohydrates content was deduced by difference with other components assuming that  
157 vitamins were weakly represented (Felfoul et al., 2020).

158

## 159 2.4. Particle size distribution

160 Particle size distributions of powders were determined with a laser granulometer  
161 (Mastersizer 2000 Malvern Instruments, UK), equipped with He-Ne laser (632.8 nm  
162 wavelength), using the Aero S module for dry dispersion in the following conditions: 2 bar; 100  
163 % air pressure; 100 % feed rate; 3 mm hopper gap. The mean diameter in volume was chosen  
164 as particle size estimator. Classical granulometric parameters  $D_{10}$ ,  $D_{50}$ , and  $D_{90}$  were recorded  
165 ( $D_X$  corresponds to the size for which X % of the particle population has smaller size). Span  
166 was calculated to evaluate the width of the particle size distribution (equation 1) (Felfoul et al.,  
167 2020):

$$168 \text{Span} = (D_{90} - D_{10})/D_{50} \text{ Equation (1)}$$

## 169 2.5. Flow properties of skim dromedary and cow's milk powders

170 Powder flowability was evaluated using the FT4 powder rheometer (Freeman  
171 Technology, Worcestershire, UK) as previously reported in the literature (Freeman & Fu, 2008;  
172 Freeman, 2011). Stability, compressibility, and rotational shear tests were performed according  
173 to the FT4 standard methods. For each test, a powder sample was poured into a FT4 cylindrical  
174 vessel of 50 mm diameter. To ensure analytical reproducibility, FT4 analyses include a  
175 preliminary step of powder conditioning, performed by a rotational and vertical moving (both  
176 downwards and upwards) through the powder sample of a blade (5° helix angle and 48.0 mm  
177 diameter) at constant tip speed of 60 mm.s<sup>-1</sup>. This operation removes any packing history such  
178 as pre-consolidation or excess entrapped air and generates a uniform powder packing in order  
179 to ensure repeatable and comparable data (Freeman, Cooke, & Schneider, 2009). The mass of  
180 skim milk powders was automatically recorded by the FT4 apparatus. The different tests carried  
181 out with the FT4 powder rheometer are described hereafter.

182

183

### 184 **2.5.1. Stability test**

185 The stability test is designed to assess the flow energy changes upon repeated testing, it  
186 consists in seven successive conditioning and test cycles. Stability test cycles were conducted  
187 by the rotating movement of the blade into and through a powder bed contained in the  
188 measurement cell (85 mL glass cylinder of 50 mm diameter) at  $100 \text{ mm.s}^{-1}$  tip speed and  $5^\circ$   
189 helix angle. During both downwards and upwards rotational movement of the blade, the torque  
190 (related to shear stress  $\tau$ ) and axial force (related to normal stress  $\sigma$ ) required to move the blade  
191 through the powder were recorded and used to calculate the total energy input required to make  
192 the powder bed flow. The basic flowability energy (BFE), corresponding to the stabilized flow  
193 energy, was evaluated as the flow energy required to displace a conditioned powder sample  
194 during downwards movement of the blade in the seventh test cycle (Freeman, 2007). The bulk  
195 density (BD) was also obtained from the stability test and was calculated as the ratio of sample  
196 mass to vessel volume (85 mL).

197 The specific energy (SE) is the energy needed to displace the conditioned powder bed  
198 during upwards testing divided by the mass of analyzed powder sample (Equation 2). This gives  
199 an indication of powder flow properties in a loosely packed and unconfined state (Mitra et al.,  
200 2017). SE is mostly related to intrinsic particle properties, such as cohesion, particle size and  
201 shape distributions, and surface roughness.

$$202 \quad SE = (\text{upwards flow energy of cycle 6} + \text{upwards flow energy of cycle 7}) / (2 \times \text{split mass})$$

203 (Equation 2)

### 204 **2.5.2. Compressibility**

205 The compressibility test evaluates the change in powder density according to applied  
206 normal stress. A powder sample was first placed in the measurement cell (i.e. two overlaid  
207  $50 \text{ mm} \times 85 \text{ mL}$  glass cylinders) and submitted to three conditioning cycles performed as  
208 previously described. After that, the vessel was split to remove any excess powder and the  
209 dynamic blade was replaced by the 48 mm vented piston. Then, powder was slowly compressed

210 by the vented piston vertically moving at  $0.05 \text{ mm.s}^{-1}$  and applying normal stresses  $\sigma$  from 0.5  
211 to 15 kPa (0.5, 1, 2, 4, 6, 8, 10, 12, and 15 kPa) while measuring its volume change. After  
212 reaching equilibrium at the target stress, the distance traveled by the vented piston was  
213 measured and the compressibility was calculated as a percentage change in volume after  
214 compression ( $C_p$ ). Compressibility is indicative of the level of cohesion between particles  
215 (Freeman, 2007; Bian, Ambrose, & Subramanyam, 2015). Compressed bulk density (CBD) is  
216 calculated from bulk density (BD) and compressibility (Equation 3).

$$217 \quad CBD = \frac{BD}{1 - \frac{C_p}{100}} \quad (\text{Equation 3})$$

### 218 **2.5.3. Shear cell test**

219 Shear cell measurements are widely used to evaluate the flowability of powders in high-  
220 shear applications. The rotational shear cell of the FT4 powder rheometer consists of a vessel  
221 containing the powder samples and a FT4 shear head applying both normal and rotational shear  
222 stresses to the powder bed. Powder sample was first conditioned using the helical blade as  
223 previously described (Quintanilla, Castellanos, & Valverde, 2001). After the conditioning step,  
224 powder sample was slowly subjected for 60 s to a normal stress of 9 kPa carried out with a  
225 vented piston vertically moving at a maximum speed of  $0.08 \text{ mm.s}^{-1}$ . Then, the vessel  
226 containing the powder sample was split, the vented piston was changed for the shear cell head,  
227 and the powder sample was recompressed at 9 kPa to remove any disturbances caused by the  
228 split and ensure that the powder bed surface was properly consolidated. The preconsolidated  
229 powder sample was then submitted to a preshearing stage (60 s at 9 kPa normal stress) carried  
230 out with the rotational shear cell accessory (48 mm diameter), to achieve a critically  
231 consolidated state. The normal stress was then reduced lowered and the incipient shear stress  
232 necessary to cause powder bed failure and initiate flow was measured. The preshear/shear  
233 sequence was repeated five times at decreasing normal stresses  $\sigma$  from 7 to 3 kPa by 1 kPa steps

234 at 18°.min<sup>-1</sup> rotational speed. The curve representing the evolution of incipient shear stress with  
 235 applied normal stress is thus the so-called yield locus (Gnagne, Petit, Gaiani, Scher, Amani,  
 236 2017). Shear cell parameters, major principal stress (MPS), unconfined yield stress (UYS),  
 237 cohesion, and flow function (FF), were then determined with the FT4 software by the Mohr  
 238 circle approach using following equations 4-6 (ASTM, 2004, 2005).

$$239 \quad MPS = \frac{(\sigma_x + \sigma_y)}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad (\text{Equation 4})$$

240 Where:

241  $\tau_{xy}$ : incipient shear stress (Pa),  $\sigma_x$ : stress at horizontal axis (Pa),  $\sigma_y$ : stress at vertical axis (Pa)

$$242 \quad UYS = P/A \quad (\text{Equation 5})$$

243 Where P: axial load at failure (N),

$$244 \quad A = \frac{A_0}{1 - \varepsilon} = \text{corrected area (m}^2\text{)}$$

245 With:  $A_0$  is the initial horizontal area of the powder bed (m<sup>2</sup>) and  $\varepsilon$  designates the axial strain  
 246 of powder sample (s<sup>-1</sup>).

247 The cohesion was evaluated as the intercept of the linear regression of the yield locus curve.

248 The flow factor (FF) is the most commonly used parameter for the description of powder  
 249 flowability (Bian, Ambrose, & Subramanyam, 2015). (Equation 6):

$$250 \quad FF = \frac{MPS}{UYS} \quad (\text{Equation 6})$$

251 The higher the flow factor, the better the powder flows. Powders were classified by Jenike  
 252 (1980) according to FF values as follows:

- 253 -  $FF < 1$ : not flowing,
- 254 -  $1 < FF < 2$ : very cohesive,
- 255 -  $2 < FF < 4$ : cohesive,
- 256 -  $4 < FF < 10$ : easy-flowing,

1  
2  
3 257 10 < FF: free-flowing.  
4

5 258 **2.6. Statistical analysis**  
6

7  
8 259 All analyses were carried out in triplicates and reported values were means  $\pm$  standard  
9  
10 260 deviations. Statistical analysis was performed using the DSAASTAT add-on for Excel 2010  
11  
12 261 (Microsoft, Redmond, USA). The presence of significant differences between sample results  
13  
14 262 was investigated by one-way ANOVA and the means were separated by Tukey's HSD test at  $p$   
15  
16 263  $\leq 0.05$ . Pearson's correlation coefficients ( $r$ ) were calculated to evaluate the degree of  
17  
18 264 correlation between investigated powder physicochemical and functional properties.  
19  
20

21  
22 265 **3. RESULTS AND DISCUSSION**  
23

24 266 **3.1. Proximate composition of dromedary and cow's skim milks and milk**  
25  
26 267 **powders**  
27

28  
29 268 The proximate composition of spray-dried powders is displayed in Table 2. The total  
30  
31 269 solids, as well as fat, ash, and carbohydrate contents were significantly different between  
32  
33 270 produced powders. Moisture contents ranged between 2.98 and 7.04 % (w/w) on wet basis for  
34  
35 271 skim dromedary milk powders and between 3.37 and 5.56 % (w/w) on wet basis for skim cow's  
36  
37 272 milk powders. Generally, moisture content lower than 10 % (w/w) ensures powder stability  
38  
39 273 during storage (Kaur, Kaushal, & Sandhu, 2011). When increasing the air outlet temperature  
40  
41 274 during spray-drying of both milk powders, the moisture content significantly decreased  
42  
43 275 whatever the milk type (cf. Table 2). This could be explained by the higher rate of evaporated  
44  
45 276 water and the lower feed rate in C2 conditions (85 °C air outlet temperature and 65 mL.min<sup>-1</sup>  
46  
47 277 feed flow-rate) compared to C1 conditions (75 °C air outlet temperature and 75 mL.min<sup>-1</sup> feed  
48  
49 278 flow-rate). The protein content of the dromedary and cow's milk powders did not exhibit any  
50  
51 279 significant difference. As the outlet air temperature was increased from 75 to 85 °C, the  
52  
53 280 carbohydrates content increased from 53.74 to 55.66 % (w/w) on dry basis for skim dromedary  
54  
55 281 milk powder, while it decreased from 51.31 to 50.71 % (w/w) on dry basis for skim cow's milk  
56  
57  
58  
59  
60

1  
2  
3 282 powder. Also, upon air outlet temperature increase, the ash content decreased from 10.74 to  
4  
5 283 8.90 % (w/w) on dry basis for dromedary milk powders and from 6.63 to 6.41 % (w/w) on dry  
6  
7 284 basis for cow's milk powders. This reduction of ash content could result from calcium phosphate  
8  
9 285 precipitation during the manufacture of skim milk powder (Lin, Kelly, O'Mahony, & Guinee,  
10  
11 286 2018). Fat contents ranged between 12 and 16 % (w/w) on dry basis for skim dromedary and  
12  
13 287 cow's milk powders, respectively. These rather high fat contents (> 2 % on dry basis) suggested  
14  
15 288 that studied powders should be considered as partially skim milk powders. These results could  
16  
17 289 be justified by the fact that the conditions used for milk skimming by centrifugation in this  
18  
19 290 study were soft compared to what is commonly realized in the literature using a cream separator  
20  
21 291 (Heymann, 2016). Spray-drying conditions did not have a significant impact on the proximate  
22  
23 292 composition of studied milk powders. As it can be seen from Table 2, the proximate  
24  
25 293 compositions of skim milk powders were comparable to those of their corresponding milks.

26  
27  
28  
29  
30 294 Table 2 shows the water activity values of partially skim dromedary and cow's spray-  
31  
32 295 dried milks. Water activity was significantly influenced by spray-drying conditions whatever  
33  
34 296 the milk type: it was lower when milks were spray-dried in C2 conditions at 85 °C air outlet  
35  
36 297 temperature (0.203 and 0.274 for partially skim dromedary and cow's milk powders,  
37  
38 298 respectively) than in C1 conditions at 75 °C air outlet temperature (0.391 and 0.385 for partially  
39  
40 299 skim dromedary and cow's milk powders, respectively). These results agreed with Zouari et al.  
41  
42 300 (2019) who reported that water activity of skim dromedary milk powder was lower when spray-  
43  
44 301 dried at 200 °C inlet air temperature compared to 160 and 180 °C air inlet temperatures.  
45  
46 302 Otherwise, Sulieman, Elamin, Elkhalifa, and Laleye (2014) showed that the concentration,  
47  
48 303 temperature, direction of the feed, and milk type did not affect water activity of dromedary milk  
49  
50 304 powders spray-dried at 200 – 220 °C air inlet temperature and 98 - 105 °C air outlet temperature,  
51  
52 305 but it gave different results for cow's milk powders spray-dried in the same conditions. Indeed,  
53  
54  
55  
56  
57  
58  
59  
60



1  
2  
3 306 the ideal temperature range for spray-drying cow's milk are 175 - 240 °C for air inlet  
4  
5 307 temperature and 70 - 90 °C for air outlet temperature (Schuck, Jeantet, Dolivet, 2012).  
6

### 7 308 **3.2. Particle size distribution of dromedary and cow's milk powders**

9  
10 309 The granulometric characteristics of powders are shown in Table 3. All powders  
11  
12 310 exhibited monomodal particle size distributions centered around 14 - 20 µm (Figure 1),  
13  
14 311 consistently with previous results obtained with the same combination of pilot spray-dryer and  
15  
16 312 bi-fluid nozzle (Guérin et al., 2017; Khanji et al., 2018). It should be mentioned that a significant  
17  
18 313 effect of both milk type and spray-drying conditions was observed on the particle size  
19  
20 314 distribution of spray-dried milk powders. The median particle sizes ( $D_{50}$ ) as well as the particle  
21  
22 315 size distributions of spray-dried milk powders significantly differed according to spray-drying  
23  
24 316 conditions and milk type. As for the milk type, significantly higher median particle sizes ( $D_{50}$ )  
25  
26 317 were obtained for partially skim cow's milk powders whatever the spray-drying conditions.  
27  
28 318 This result could be explained by the difference in fat content between milk samples (Table 2):  
29  
30 319 indeed, partially skim cow's milk being richer in lipids, obtained powder was expected to be  
31  
32 320 stickier and then have a higher tendency to form agglomerates, leading to increased median  
33  
34 321 particle size. This hypothesis was confirmed by the significantly higher fines proportion of  
35  
36 322 partially skim cow's milk powders whatever the spray-drying conditions. As regards the  
37  
38 323 influence of spray-drying conditions, when increasing the air outlet temperature, median  
39  
40 324 particle size of partially skim **dromedary and** cow's milk powder was significantly higher but  
41  
42 325 no significant effect was observed for partially skim dromedary milk powders (Table 3). The  
43  
44 326 results obtained for skim cow's milk powders could be attributed to the fact that a higher drying  
45  
46 327 temperature and a lower feed-rate accelerates the drying rate of droplets, promoting the fast  
47  
48 328 formation of a crust at their surface and therefore limit shrinkage, which leads to larger particles  
49  
50 329 (Kim, Chen, & Pearce, 2002). The fact that the particle size distribution of skim dromedary  
51  
52 330 milk was unaffected by spray-drying conditions may be an indication that crust formation did  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 331 not occur upon drying of sprayed droplets, presumably owing to the protein content and casein  
4  
5 332 proportions differing from cow's milk (Felfoul et al., 2017 ; Lajnaf et al., 2017). Moreover,  
6  
7 333 these results confirm that feed flow-rate may have a minor influence on particle size distribution  
8  
9 334 of spray-dried skim milk powders, as particle size distributions obtained in all spray-drying  
10  
11 335 conditions remained close.

12  
13  
14 336 The span was rather close for all spray-dried milk powders, which showed that milk  
15  
16 337 type or spray-drying conditions did not have a great influence on the range of obtained particle  
17  
18 338 sizes. However, there was no marked effect of either the milk type or the spray-drying  
19  
20 339 conditions on the span of spray-dried milk powders.

### 21 22 23 340 **3.3. Basic flowability energy, bulk density, and specific energy**

24  
25 341 Mean BFE values obtained from the stability test are presented in Table 4. BFE is known  
26  
27 342 to be a key parameter that expresses powder flowability in low-stress environments (Freeman,  
28  
29 343 2007). It is generally observed that powders exhibiting low BFE values have good flow  
30  
31 344 properties and inversely, high BFE is often obtained for powders that poorly flow. The BFE of  
32  
33 345 partially skim dromedary and cow's milk powders ranged from 620 to 1018 mJ. The air outlet  
34  
35 346 temperature during spray-drying as well as the milk type exhibited noticeable effects on BFE  
36  
37 347 values. On one hand, partially skim dromedary milk powders had significantly lower BFE  
38  
39 348 values than partially skim cow's milk powders, denoting a better flowability of the former. On  
40  
41 349 the other hand, BFE of partially skim cow's milk powders was about 900 mJ whatever the spray-  
42  
43 350 drying conditions, whereas BFE of partially skim dromedary milk powders was well higher in  
44  
45 351 C2 conditions (1 018 mJ) than in C1 conditions (620 mJ).

46  
47 352 Besides, milk type had significant effects on the BD values of spray-dried milk powders,  
48  
49 353 contrarily to spray-drying temperature that showed no significant impact on BD. Whatever the  
50  
51 354 spray-drying conditions; partially skim dromedary milk powders had significantly higher BD  
52  
53 355 values than partially skim cow's milk powders, i.e. 0.31 vs. 0.24 g.mL<sup>-1</sup>, respectively (Table 4).

1  
2  
3 356 These differences could be attributed to milk powder proximate composition, particle  
4  
5 357 size or shape (Jan, Ghoroi, & Saxena, 2017). Indeed, higher contents in sticky material, mainly  
6  
7 358 lipids, were observed for partially skim cow's milk powders. The presence of surface lipids is  
8  
9 359 expected to make particles stickier, thus increasing powder cohesion and decreasing bulk  
10  
11 360 density. Overall, BFE and BD of spray-dried milk powders, and thus flowability in low stress  
12  
13 361 conditions, was essentially influenced by particle size along with fat content.  
14  
15

16  
17 362 Specific energy indicates how easily powders flow in an unconfined environment and it  
18  
19 363 gives a good indication of the level of powder cohesion (Freeman, Cooke, & Schneider, 2009).  
20  
21 364 SE of partially skim dromedary and cow's milk powders ranged from 8.49 to 15.59 mJ/g, which  
22  
23 365 corresponds to moderate-to-high cohesion (Bharadwaj, Ketterhagen, & Hancock, 2010). SE  
24  
25 366 values were significantly affected by spray-drying conditions and milk type, as shown in Table  
26  
27 367 4. As for milk type, significantly higher SE values, indicating a poorer flowability, were  
28  
29 368 obtained for partially skim cow's milk powders whatever the spray-drying conditions. As  
30  
31 369 regards the influence of spray-drying conditions, SE of partially skim dromedary's milk  
32  
33 370 powders significantly increased in C2 conditions, indicating poorer flow properties. On the  
34  
35 371 contrary, spray-drying conditions had no significant effect on the SE of partially skim cow's  
36  
37 372 milk powders, indicating that they did not affect the flowability of cow's milk powder. The  
38  
39 373 lower SE of partially skim dromedary's milk powder spray-dried in C1 conditions (8.49 mJ/g)  
40  
41 374 could be explained by differences in surface composition (Felfoul et al., 2020). Surface  
42  
43 375 composition of powder particles plays an important role in its flow behavior because flowability  
44  
45 376 involves overcoming surface interactions between powder particles (Fitzpatrick, Barringer, &  
46  
47 377 Iqbal, 2004). Kim, Chen & Pearce (2002) reported that a higher surface fat content might  
48  
49 378 explain the lower flow properties of industrial spray-dried milk powders. Thereby, studied  
50  
51 379 partially skim cow's milk powders, having significantly higher fat contents than partially skim  
52  
53 380 dromedary milk powders, had poorer flow powders whatever the spray-drying conditions.  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 381 Based results obtained from the stability test (BD, BFE, and SE), the flow behavior of  
4  
5 382 studied milk powders could be sorted as follows, from poorer to better flowability: Cow\_C1  $\approx$   
6  
7  
8 383 Cow\_C2 < Dromedary\_C2 < Dromedary\_C1.  
9

#### 10 384 **3.4 Compressibility**

11  
12 385 Compressibility logically increased with applied normal stress for all investigated  
13  
14 386 powders (cf. Figure 2). This behavior is expected to be due to the closer particle packing and  
15  
16 387 the increase in interparticle surface contact at increased applied normal stress (Bian, Ambrose,  
17  
18 388 & Subramanyam, 2015; Jan, Ghoroi, & Saxena, 2017). Compressibilities at 15 kPa ranged  
19  
20 389 between 34.24 and 49.12 %, showing that studied powders were highly compressible, which  
21  
22 390 was in line with the poor flowing properties of spray-dried powders that has already been  
23  
24 391 evidenced with BFE and SE values. ~~The outlet air temperature during spray-drying as well as~~  
25  
26 392 ~~the~~ The milk type had noticeable effects on powder compressibility at 15 kPa, as displayed by  
27  
28 393 Table 4. ~~In addition, the~~ The higher the air outlet temperature applied during spray-drying of  
29  
30 394 dromedary milk, the higher the compressibility at 15 kPa normal stress. ~~On the contrary, for~~  
31  
32 395 ~~For~~ partially skim cow's milk powders, no significant difference of compressibility and CBD  
33  
34 396 could be attributed to spray-drying conditions. Moreover, partially skim dromedary milk  
35  
36 397 powders were less compressible than partially skim cow's milk powder whatever the spray-  
37  
38 398 drying conditions; this could be related to the better flow properties of partially skim dromedary  
39  
40 399 milk powder and to the higher fat content of partially skim cow's milk powder (Table 2).  
41  
42 400 Compressibility of studied milk powders increased in the following order: Dromedary\_C1 <  
43  
44 401 Dromedary\_C2 < Cow\_C1  $\approx$  Cow\_C2, confirming the classification established on the basis  
45  
46 402 of BFE and SE values. Compressibility at 15 kPa was significantly positively correlated to BFE  
47  
48 403 and SE (Pearson's correlation coefficients  $r$  equaled 0.74 and 0.99, respectively, cf. Table 5).  
49  
50 404

51  
52 405 Compressibility at 15 kPa was also positively correlated to fat content (Pearson's  
53  
54 406 correlation coefficient  $r$  of 0.80, cf. Table 5). Then, the higher the fat content, the more  
55  
56  
57  
58  
59  
60

1  
2  
3 406 compressible the studied milk powder. Fat could act as lubricating agent at the surface of large  
4  
5 407 particle but not at the surface of small particles as reducing particle size increases the contact  
6  
7 408 area between particles allowing greater interaction between particles and thus higher cohesive  
8  
9 409 forces (Fitzpatrick, Barringer, & Iqbal, 2004). In addition, fine particles exhibit higher  
10  
11 410 compressibility because of their greater specific surface area and the fewer interparticular voids  
12  
13 411 (Jan, Ghoroi, & Saxena, 2017). Gnagne, Petit, Gaiani, Scher, & Amani (2017) reported that  
14  
15 412 powders with a higher fine particle content and irregular morphology are likely to be more  
16  
17 413 susceptible to compression than more spherical, larger particles. These findings are in  
18  
19 414 disagreement with the results obtained in the present study, where it was observed that cow's  
20  
21 415 milk particles, of greater median size and having a higher fat content, were more compressible.  
22  
23 416 In the case of the present study, the usual negative impact of particle size on powder  
24  
25 417 compressibility is overcome by the high influence of fat content on powder cohesion, and thus  
26  
27 418 on its sensitivity to compression. However, it is worth noting that compressibility was positively  
28  
29 419 correlated with median particle size and BFE ( $r = 0.80$  and  $0.74$ , respectively, Table 5). It has  
30  
31 420 been reported that particle size and milk powder composition, mainly fat content, were the key  
32  
33 421 factors influencing powder flowability. ~~This confirms that the particle shape as well as the milk~~  
34  
35 422 ~~powder composition, mainly fat content, are the main factors determining the flow behavior of~~  
36  
37 423 ~~studied milk powders.~~

### 424 3.5. Shear properties

425 The yield locus of partially skim dromedary and cow's milk powders are presented in  
426 Figure 3. Incipient shear stress logically increased with applied normal stress. Spray-drying  
427 conditions and milk type significantly influenced the shear flow properties of spray-dried  
428 powders (Table 4). Partially skim cow's milk powders were more cohesive (around 5 kPa  
429 cohesion) than partially skim dromedary milk powders (around 4 kPa cohesion) whatever the  
430 spray-drying conditions, indicating a poorer flowability of partially skim cow's milk powders,

1  
2  
3 431 in agreement with previously evoked flow properties and the higher fat content of partially skim  
4  
5 432 cow's milk. No significant effect of the air outlet temperature was denoted on the cohesion and  
6  
7 433 FF values of the investigated powders. ~~Similarly, no significant effect of the outlet air~~  
8  
9 434 ~~temperature on the FF values was also observed~~, showing that both milk powders were  
10  
11 435 extremely cohesive regardless of the applied spray-drying conditions. ~~According to Jenike's~~  
12  
13 436 ~~classification all produced powders came under the category of very cohesive material~~ and thus  
14  
15 437 exhibited very poor flow properties. Shear and compressibility test results were in good  
16  
17 438 agreement, i.e. the higher the powder cohesion, the lower the FF values, the more compressible  
18  
19 439 the powder bed. Based on stability, compressibility, and shear tests, the flow behavior of all  
20  
21 440 studied powders could be sorted as follows, from poorer to better flowability: Cow\_C1 ≈  
22  
23 441 Cow\_C2 < Dromedary\_C2 < Dromedary\_C1. Possible reasons for this classification could be  
24  
25 442 the differences in milk composition (mainly fat content), particle size, particle interlocking,  
26  
27 443 packing of smaller particles in void spaces, and surface irregularity, enabling higher cohesive  
28  
29 444 interactions (Fitzpatrick, Barringer, & Iqbal, 2004; Siliveru, Kwek, Lau, & Ambrose, 2016;  
30  
31 445 Siliveru, Jange, Kwek, Ambrose, 2017; Jan, Ghoroi, & Saxena, 2017). In the case of the present  
32  
33 446 study, fat content could justify observed differences in flowability, as it was higher for partially  
34  
35 447 skim cow's milk powder than for partially skim dromedary's milk powder (about 16 vs. 12 %  
36  
37 448 (w/w) on dry basis, respectively, cf. Table 2). Significant correlations of cohesion and FF to fat  
38  
39 449 content (Pearson's correlation coefficients  $r$  of 0.99 and 0.97, respectively, cf. Table 5) were  
40  
41 450 obtained, indicating that the presence of fat was surely the main reason of flowability  
42  
43 451 impairment of studied powders. Significantly positive correlations of cohesion and FF to  
44  
45 452 particle size (Pearson's correlation coefficients  $r$  of 0.88 and 0.77, respectively, cf. Table 5)  
46  
47 453 were also evidenced. This suggests that particle morphology (more specifically particle size  
48  
49 454 distribution) significantly impacted flowability of studied powders, consistently with Babu,  
50  
51 455 Siliveru, Amamcharla, Vadlani, and Ambrose (2018). Teunou, Fitzpatrick, and Synnott (1999)  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 456 also studied the flowability of milk powders differing in particle size and composition (skim  
4  
5 457 milk and whey powders), concluding that the particle size significantly affects flowability:  
6  
7 458 smaller particles possess more contact points with the neighboring particles, thus making  
8  
9 459 rearrangements of the powder bed more difficult and impairing its flowability. The poor  
10  
11 460 flowability of milk powders was also probably due to their irregular surface particles, leading  
12  
13 461 to increased interparticular interactions and particle interlocking (Hart, 2015). Similar  
14  
15 462 observations were reported for different pharmaceutical powders by Lindberg et al. (2004).

#### 19 463 **4. CONCLUSION**

21 464 The spray-drying process has a significant impact on milk powder flow properties. In  
22  
23 465 this study, partially skim dromedary and cow's milks were spray-dried in different conditions  
24  
25 466 (of air outlet temperature and feed flow-rate) without prior concentration to avoid introducing  
26  
27 467 another source of process variability. Partially skim dromedary and cow's milk powders were  
28  
29 468 very cohesive. The spray-drying conditions, the milk type, the particle size distribution as well  
30  
31 469 as the residual fat content showed a great influence on flow properties of partially skim  
32  
33 470 dromedary and cow's milk powders. Using a higher air outlet temperature (85 °C) led to poorer  
34  
35 471 flowability and higher compressibility whatever the milk type. Shear tests showed that partially  
36  
37 472 skim cow's milk powders were more cohesive than partially skim dromedary milk powders.  
38  
39 473 The shear flow properties of milk powders are expected to be influenced by fat content, particle  
40  
41 474 size distribution, particle morphology, particle interlocking, packing of smaller particles in void  
42  
43 475 spaces, and surface irregularity. Furthermore, in order to help industrializing dromedary milk  
44  
45 476 powder production, further investigations should focus on biochemical and technological  
46  
47 477 (gelation, coagulation, etc.) properties of dromedary milk powders.

#### 54 478 **CONFLICT OF INTEREST**

57 479 The authors declare no conflict of interest.

## 480 **ACKNOWLEDGMENTS**

481 This project was financially supported by the Ministry of Higher Education and  
482 Scientific Research of Tunisia through the scholarship program under the project called  
483 Mobility to Encourage Young Tunisian Researchers (N° 18PJEC12-20, 2018). The authors  
484 acknowledge also support of the LIBio by the "Impact Biomolecules" project of the "Lorraine  
485 Université d'Excellence" (Investissements d'avenir – ANR). The authors would also like to  
486 thank all the LIBio members for their help and support as well as Alexandre Laflotte from the  
487 experimental domain of La Bouzule for cow's milk supply.

## 488 **ETHICAL STATEMENT**

489 This research study does not include animal and human testing.

## 490 **DATA AVAILABILITY STATEMENT**

491 We declare that the data that support the findings of this study are openly available for all useful  
492 purposes.

## 493 **REFERENCES**

494 A.O.A.C. (2016). Official methods of analysis of AOAC International (20th ed.).  
495 Rockville, Maryland, USA: AOAC international.

496 Al-Juboori, A. T., Mohammed, M., Rashid, J., Kurian, J., & El Refaey, S. (2013).  
497 Nutritional and medicinal value of camel (*Camelus dromedarius*) milk. *Food and Environment*  
498 *Ii: The Quest for a Sustainable Future*, 170, 221-232.

499 ASTM (2004). One-Dimensional Consolidation Properties of Soils Using Incremental  
500 Loading.

501 ASTM D2435-04, West Conshohocken, PA. ASTM (2005). Standard test method for  
502 unconfined compressive strength of cohesive soil. D2166, West Conshohocken, PA.



- 1  
2  
3 503 Babu, K. S., Siliveru, K., Amamcharla, J. K., Vadlani, P. V., & Ambrose, R. P. K.  
4  
5 504 (2018). Influence of protein content and storage temperature on the particle morphology and  
6  
7 505 flowability characteristics of milk protein concentrate powders. *Journal of Dairy Science*, *101*,  
8  
9 506 1-14.
- 10  
11  
12 507 Bharadwaj, R., Ketterhagen, W. R., & Hancock, B. C. (2010). Discrete element  
13  
14 508 simulation study of a Freeman powder rheometer. *Chemical Engineering Science*, *65*, 5747–  
15  
16 509 5756.
- 17  
18  
19 510 Bian, Q., Ambrose, R. P. K., & Subramanyam, Bh. (2015). Effect of chaff on bulk flow  
20  
21 511 properties of wheat. *Journal of Stored Products Research*, *64*, 21–26.
- 22  
23  
24 512 Ceballos, A. M., Giraldo, G. I., & Orrego, C.E. (2012). Effect of freezing rate on quality  
25  
26 513 parameters of freeze-dried soursop fruit pulp. *Journal of Food Engineering*, *111*, 360–365.
- 27  
28  
29 514 Esquivel, P., & Jiménez, V. M. (2012). Functional properties of coffee and coffee by-  
30  
31 515 products. *Food Research International*, *46*, 488–495.
- 32  
33  
34 516 Felfoul, I., Jardin, J., Gaucheron, F., Attia, H., & Ayadi, M. A. (2017). Proteomic  
35  
36 517 profiling of camel and cow milk proteins under heat treatment. *Food Chemistry*, *216*, 161-169.
- 37  
38 518 Felfoul, I., Burgain, J., Perroud, C., Gaiani, C., Scher, J., Attia, H., & Petit,  
39  
40 519 J. (2020). Impact of spray-drying conditions on physicochemical properties and rehydration  
41  
42 520 ability of skim dromedary and cow's milk powders, *Drying*  
43  
44 521 *Technology*. DOI: [10.1080/07373937.2020.1828448](https://doi.org/10.1080/07373937.2020.1828448)
- 45  
46  
47 522 Fitzpatrick, J. J., Barringer, S. A., & Iqbal, T. (2004). Flow property measurement of  
48  
49 523 food powders and sensitivity of Jenike's hopper design methodology to the measured values.  
50  
51 524 *Journal of Food Engineering*, *61*, 399– 405.
- 52  
53  
54 525 Fitzpatrick, J. J., Barry, K., Cerqueira, P. S. M., Iqbal, T., O'Neill, J., & Roos, Y. H.  
55  
56 526 (2007). Effect of composition and storage conditions on the flowability of dairy powders.  
57  
58 527 *International Dairy Journal*, *17*, 383–392.
- 59  
60

- 1  
2  
3 528 Folch, J., Lees, M., & Sioane-Staniey, G. A. (1957). A simple method for isolation and  
4  
5 529 purification of total lipids from animal tissues. *Journal of Biological Chemistry*, 266, 497 - 509.  
6  
7  
8 530 Freeman, R. (2007). Measuring the flow properties of consolidated, conditioned and  
9  
10 531 aerated powders—a comparative study using a powder rheometer and a rotational shear cell.  
11  
12 532 *Powder Technology*, 174, 25–33.  
13  
14 533 Freeman, R. E., Cooke, J. R., & Schneider, L. C. R. (2009). Measuring shear properties  
15  
16 534 and normal stresses generated within a rotational shear cell for consolidated and non-  
17  
18 535 consolidated powders. *Powder Technology*, 190, 65–69.  
19  
20  
21 536 Freeman, R., & Fu, X. (2008). Characterisation of powder bulk, dynamic flow and shear  
22  
23 537 properties in relation to die filling. *Powder Metallurgy*, 51, 196–201.  
24  
25  
26 538 Freeman, T. (2011). Characterizing Powder Flow. *Chemical Engineering Journal*, 118,  
27  
28 539 66-72.  
29  
30 540 Gaiani, C., Morand, M., Sanchez, C., Tehrany, E. A., Jacquot, M., & Schuck, P. (2010).  
31  
32 541 How surface composition of high milk proteins powders is influenced by spray-drying  
33  
34 542 temperature. *Colloids and Surfaces B: Biointerfaces*, 75, 377–384.  
35  
36  
37 543 Gnagne, E. H., Petit, J., Gaiani, C., Scher, J., & Amani, G. N. (2017). Characterisation  
38  
39 544 of flow properties of foutou and fougou flours, staple foods in West Africa, using the FT4  
40  
41 545 powder rheometer. *Journal of Food Measurement and Characterization*, 11, 1128–1136.  
42  
43  
44 546 Guerin, J., Petit, J., Burgain, J., Borges, F., Bhandari, B., Perroud, C., Desobry, S.,  
45  
46 547 Scher, J., & Gaiani, C. (2017). Lactobacillus rhamnosus GG encapsulation by spray-drying :  
47  
48 548 Milk proteins clotting control to produce innovative matrices. *Journal of Food Engineering*,  
49  
50 549 193, 10 - 19.  
51  
52  
53 550 Hammes, M. V., Englert, A. H., Noreña, C. P. Z., & Cardozo, N. S. M. (2015). Study  
54  
55 551 of the influence of soy lecithin addition on the wettability of Buffalo milk powder obtained by  
56  
57 552 spray-drying. *Powder Technology*, 277, 237-243.  
58  
59  
60

- 1  
2  
3 553 Hart, A. (2015). Effect of Particle Size on Detergent Powders Flowability and  
4  
5 554 Tableability. *Journal of Chemical Engineering and Process Technology*, 6, 215.  
6  
7 555 Ho, T. M., Chan, S., Yago, A. J. E., Shravya, R., Bhandari, B., & Bansal, N. (2019).  
8  
9 556 Changes in physicochemical properties of spray-dried camel milk powder over accelerated  
10  
11 557 storage. *Food Chemistry*, 295, 224-233.  
12  
13 558 Jan, S., Ghoroi, C., & Saxena, D. C. (2017). Characterisation of bulk and shear  
14  
15 559 properties of basmati and non-basmati rice flour in relation to flowability. *Journal of Cereal*  
16  
17 560 *Science*, 76, 215-221.  
18  
19 561 Jenike, A. W. (1964). Storage and flow of solids, Bull. No. 123. Utah Engineering.  
20  
21 562 Station, Univ. Utah, Salt Lake City.  
22  
23 563 Jenike, A. W. (1980). Storage and flow of solids. Bull. No, 123, 20<sup>th</sup> Printing, revised.  
24  
25 564 Engng. Exp. Station, Univ. of Utah, Salt Lake City (1964/1980).  
26  
27 565 Jinapong, N., Suphantharika, M., & Jamnong, P. (2008). Production of instant soymilk  
28  
29 566 powders by ultrafiltration, spray drying and fluidized bed agglomeration. *Journal of Food*  
30  
31 567 *Engineering*, 84, 194–205.  
32  
33 568 Kaur, M., Kaushal, P., & Sandhu, S. K. (2011). Studies on physicochemical and pasting  
34  
35 569 properties of Taro (*Colocasia esculenta L.*) flour in comparison with a cereal, tuber and legume  
36  
37 570 flour. *Journal of Food Science and Technology*, 50, 94–100.  
38  
39 571 Khanji, A. N., Michaux, F., Petit, J., Salameh, D., Rizk, T., Jasniewski, J., & Banon, S.  
40  
41 572 (2018). Structure, gelation, and antioxidant properties of curcumin-doped casein micelle  
42  
43 573 powder produced by spray-drying. *Food and Function*, 9, 971 - 981.  
44  
45 574 Kim, E. H. J., Chen, X. D., & Pearce, D. (2002). Surface characterization of four  
46  
47 575 industrial spray-dried powders in relation to chemical composition, structure and wetting  
48  
49 576 property. *Colloids and Surfaces B: Biointerfaces*, 26, 197–212.  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 577 Kitamura, Y., Itoh, H., & Echizen, H. (2009). Experimental vacuum spray drying of  
4  
5 578 probiotic foods, included with lactic acid bacteria. *Journal of Food Processing and*  
6  
7 579 *Preservation*, 33, 714–726.

8  
9  
10 580 Krantz, M., Zhang, H., & Zhu, J. (2009). Characterization of powder flow: Static and  
11  
12 581 dynamic testing. *Powder Technology*, 4, 239–245.

13  
14 582 Lajnaf, R., Picart-Palmade, L., Attia, H., Marchesseau, S., & Ayadi, M. A. (2017).  
15  
16 583 Foaming and adsorption behavior of bovine and camel proteins mixed layers at the air/water  
17  
18 584 interface. *Colloids and Surfaces B: Biointerfaces*, 151, 287-294.

19  
20  
21 585 Lapčík, L., Lapčíková, B., Otyepková, E., Otyepka, M., Vlček, J., Buňka, F., & Salek,  
22  
23 586 R. N. (2015). Surface energy analysis (SEA) and rheology of powder milk dairy products. *Food*  
24  
25 587 *Chemistry*, 174, 25–30.

26  
27  
28 588 Lin, Y., Kelly, A. L., O'Mahony, J.A., & Guinee, T. P. (2018). Effect of heat treatment,  
29  
30 589 evaporation and spray drying during skim milk powder manufacture on the compositional and  
31  
32 590 processing characteristics of reconstituted skim milk and concentrate. *International Dairy*  
33  
34 591 *Journal*, 78, 53-64.

35  
36  
37 592 Lindberg, N. O., Pålsson, M., Pihl, A. C., Freeman, R., Freeman, T., Zetzener, H., &  
38  
39 593 Enstad, G. (2004). Flowability measurements of pharmaceutical powder mixtures with poor  
40  
41 594 flow using five different techniques. *Drug Development and Industrial Pharmacy*, 30, 785-791.

42  
43  
44 595 Lu, H., Guo, X., Jin, Y., & Gong, X. (2018). Effect of moisture on flowability of  
45  
46 596 pulverized 503 coal. *Chemical Engineering Research and Design*, 133, 326–334.

47  
48  
49 597 Mandato, S., Rondet, E., Delaplace, G., Brkouti, A., Accart, P., Ruiz, T., Cuq, B. (2012).  
50  
51 598 Liquids atomization with two different nozzles: modelling of the effects of some processing  
52  
53 599 and formulation conditions by dimensional analysis. *Powder Technology*, 224, 323-330.

54  
55  
56  
57  
58  
59  
60

1  
2  
3 600 Mitra, H., Pushpadass, H. A., Franklin, M. E. E., Ambrose, R. P. K., Ghoroi, C., &  
4  
5 601 Battula, S. N. (2017). Influence of moisture content on the flow properties of basundi mix.  
6  
7 602 *Powder Technology*, 312, 133–143.

8  
9  
10 603 Petit, J., Méjean, S., Accart, P., Galet, L., Schuck, P., Le Floch-Fouéré, C., Delaplace,  
11  
12 604 G., & Jeantet, R. (2015). A dimensional analysis approach for modelling the size of droplets  
13  
14 605 formed by bi-fluid atomisation. *Journal of Food Engineering*, 149, 237-247.

15  
16  
17 606 Quintanilla, M. A. S., Castellanos, A., & Valverde, J. M. (2001). Correlation between  
18  
19 607 bulk stresses and interparticle contact forces in fine powders. *Physical Review E Statistical*  
20  
21 608 *Nonlinear Soft Matter Physics*, 64, 51–54.

22  
23  
24 609 Reddy, R. S., Ramachandra, C. T., Hiregoudar, S., Nidoni, U., Ram, J., & Kammar, M.  
25  
26 610 (2014). Influence of processing conditions on functional and reconstitution properties of milk  
27  
28 611 powder made from Osmanabadi goat milk by spray drying. *Small Ruminant Research*, 119,  
29  
30 612 130-137.

31  
32  
33 613 Salameh, C., Scher, J., Petit, J., Gaiani, C., Hosri, C., & Banon, S. (2016). Physico-  
34  
35 614 chemical and rheological properties of Lebanese kishk powder, a dried fermented milk-cereal  
36  
37 615 mixture. *Powder Technology*, 292, 307-313.

38  
39  
40 616 Schuck, P., Jeantet, R., & Dolivet, A. (2012). Analytical Methods for Food and Dairy  
41  
42 617 Powders; John Wiley & Sons: Oxford.

43  
44  
45 618 Siliveru, K., Jange, C. J., Kwek, J. W., & Ambrose, R. P. K. (2017). Granular bond  
46  
47 619 number model to predict the flow of fine flour powders using particle properties. *Journal of*  
48  
49 620 *Food Engineering*, 208, 11–18.

50  
51  
52 621 Siliveru, K., Kwek, J. W., Lau, G. M., & Ambrose, R. P. K. (2016). An image analysis  
53  
54 622 approach to understand the differences in flour particle surface and shape characteristics. *Cereal*  
55  
56 623 *Chemistry*, 93, 234–241.

- 1  
2  
3 624 Sulieman, A. M. E., Elamin, O. M., Elkhalfifa, E. A., & Laleye, L. (2014). Comparison  
4  
5 625 of physicochemical properties of spray-dried camel's milk and cow's milk powder.  
6  
7 626 *International Journal of Food Science and Nutrition Engineering*, 4, 15-19.  
8  
9  
10 627 Teunou, E., Fitzpatrick, J. J., & Synnott, E. C. (1999). Characterisation of food powder  
11  
12 628 flowability. *Journal of Food Engineering*, 39, 31-37.  
13  
14 629 Zouari, A., Perrone, I. T., Schuck, P., Gaucheron, F., Dolivet, A., Attia, H., & Ayadi,  
15  
16 630 M.A. (2019). Effect of outlet drying temperature and milk fat content on the physicochemical  
17  
18 631 characteristics of spray-dried camel milk powder. *Drying Technology*, 37, 1615-1624.  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Review Only

1  
2  
3 **632 Figure captions**  
4  
5

6  
7 **633 Fig. 1.** Particle size distributions of skim dromedary and cow's milk powders spray-dried at 75  
8  
9 **634** (C1) and 85 °C (C2) air outlet temperatures.  
10

11  
12 **635 Fig. 2.** Compressibility of partially skim dromedary and cow's milk powders. *Error bars*  
13  
14 **636** *represent standard deviations.*  
15

16  
17  
18 **637 Fig. 3.** Evolution of shear stress with applied normal stress for partially skim dromedary and  
19  
20 **638** cow's milk powders. *Error bars correspond to standard deviations.*  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

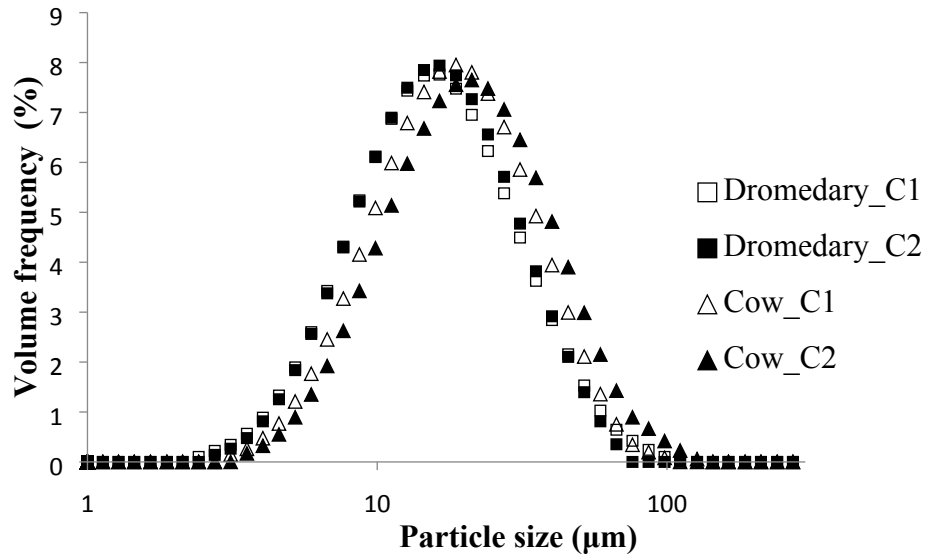


Fig. 1.



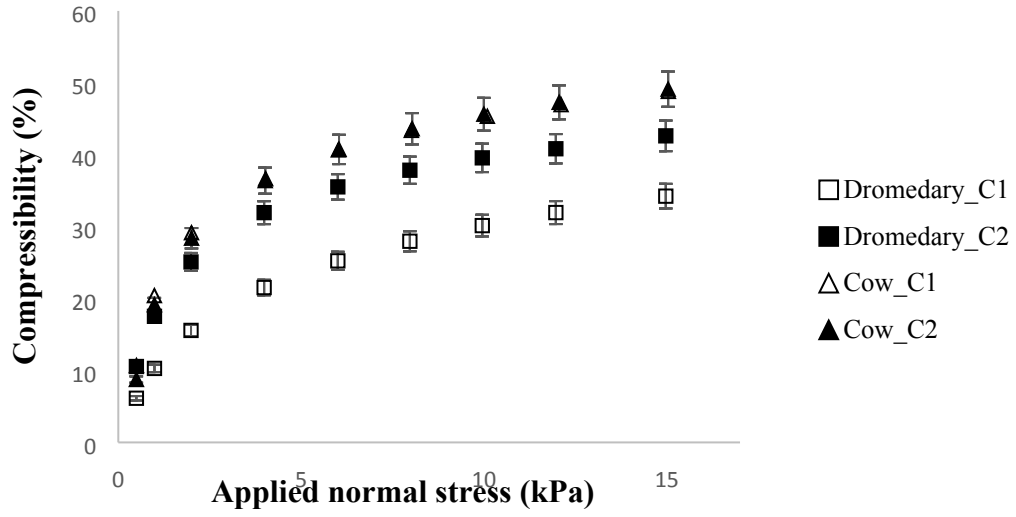


Fig. 2.

For Review Only

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

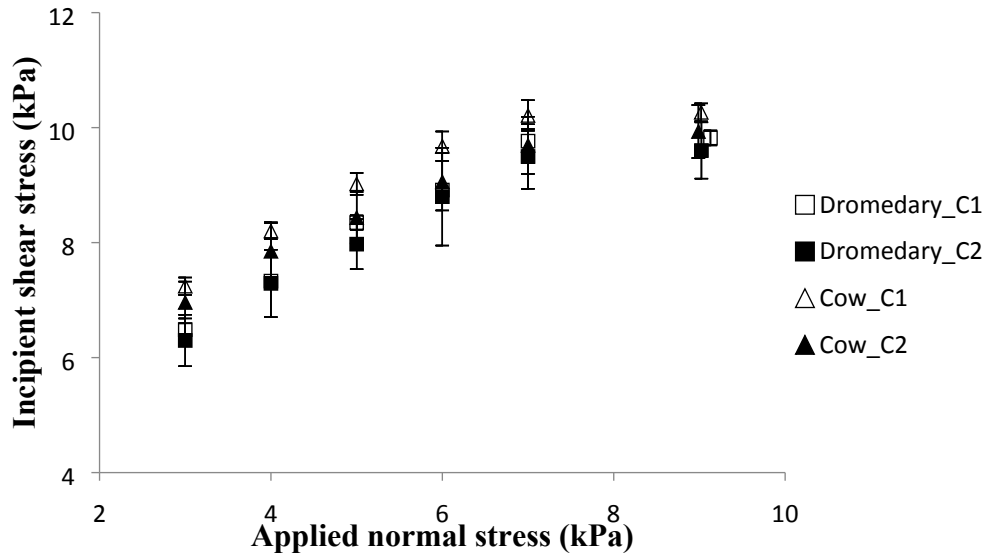


Fig. 3.

**Table 1.** Spray-drying conditions used for the production of skim dromedary and cow's milk powders.

Skim milk sample	Powder sample acronym	Spray-drying conditions	Air inlet temperature (°C)	Air outlet temperature (°C)	Feed flow rate (mL.min <sup>-1</sup> )
Dromedary	Dromedary_C1	C1	230.0 +/- 1.3	74.5 +/- 0.7	74.7 +/- 2.1
Cow	Cow_C1	C1	230.4 +/- 1.6	74.4 +/- 0.9	76.5 +/- 2.2
Dromedary	Dromedary_C2	C2	230.3 +/- 1.8	84.3 +/- 1.1	65.4 +/- 3.7
Cow	Cow_C2	C2	230.6 +/- 1.3	84.8 +/- 0.8	69.5 +/- 2.9

**Table 2.** Proximate composition of dromedary and cow's skim milks and powders produced in the two spray-drying assays.

	SDM	SCM	Dromedary_C1	Dromedary_C2	Cow_C1	Cow_C2
<b>Total solids (%(w/w) on wet basis)</b>	9.52 ± 0.51 <sup>x</sup>	12.05 ± 0.29 <sup>x</sup>	92.96 ± 0.33 <sup>c</sup>	97.01 ± 0.16 <sup>a</sup>	94.44 ± 0.12 <sup>b</sup>	96.63 ± 0.08 <sup>a</sup>
<b>Proteins (%(w/w) on dry basis)</b>	32.88 ± 1.97 <sup>x</sup>	29.46 ± 2.70 <sup>y</sup>	22.50 ± 2.48 <sup>a</sup>	23.71 ± 0.90 <sup>a</sup>	25.73 ± 2.24 <sup>a</sup>	27.00 ± 2.38 <sup>a</sup>
<b>Fat (%(w/w) on dry basis)</b>	7.35 ± 0.09 <sup>y</sup>	10.04 ± 0.13 <sup>x</sup>	12.20 ± 0.47 <sup>b</sup>	12.33 ± 1.89 <sup>b</sup>	16.35 ± 1.00 <sup>a</sup>	15.89 ± 0.68 <sup>a</sup>
<b>Ash (%(w/w) on dry basis)</b>	8.93 ± 0.04 <sup>x</sup>	6.64 ± 0.09 <sup>y</sup>	10.74 ± 0.38 <sup>a</sup>	8.90 ± 0.18 <sup>b</sup>	6.63 ± 0.23 <sup>c</sup>	6.41 ± 0.34 <sup>c</sup>
<b>Carbohydrates (%(w/w) on dry basis)</b>	50.84 ± 0.02 <sup>y</sup>	53.86 ± 0.05 <sup>x</sup>	53.74 ± 2.07 <sup>ab</sup>	55.66 ± 0.21 <sup>a</sup>	51.31 ± 2.62 <sup>b</sup>	50.71 ± 0.15 <sup>b</sup>
<b>Water activity (-)</b>	-	-	0.391 ± 0.002 <sup>a</sup>	0.203 ± 0.003 <sup>d</sup>	0.385 ± 0.002 <sup>b</sup>	0.274 ± 0.002 <sup>c</sup>

For milks and powders separately, means with different superscripted letters in the same row were significantly different according to Tukey's HSD test ( $p < 0.05$ ).

SDM: skim dromedary milk; SCM: skim cow's milk.

**Table 3.** Granulometric characteristics of skim dromedary and cow's milk powders.

	<b>Dromedary_C1</b>	<b>Dromedary_C2</b>	<b>Cow_C1</b>	<b>Cow_C2</b>
<b>D<sub>10</sub> (µm)</b>	6.41 ± 0.06 <sup>d</sup>	6.55 ± 0.10 <sup>c</sup>	7.54 ± 0.06 <sup>b</sup>	8.28 ± 0.03 <sup>a</sup>
<b>D<sub>50</sub> (µm)</b>	14.83 ± 0.08 <sup>c</sup>	14.84 ± 0.21 <sup>c</sup>	17.09 ± 0.18 <sup>b</sup>	19.19 ± 0.10 <sup>a</sup>
<b>D<sub>90</sub> (µm)</b>	35.09 ± 0.36 <sup>c</sup>	32.68 ± 0.34 <sup>d</sup>	37.43 ± 0.50 <sup>b</sup>	43.04 ± 0.33 <sup>a</sup>
<b>Span (-)</b>	1.93 ± 0.02 <sup>a</sup>	1.76 ± 0.01 <sup>c</sup>	1.75 ± 0.01 <sup>c</sup>	1.81 ± 0.01 <sup>b</sup>

Means with different superscripted letters in the same row were significantly different according to Tukey's HSD test ( $p < 0.05$ ).

**Table 4.** Flow properties issued from stability, compressibility, and shear cell tests of skim dromedary and cow's milk powders ~~deduced from the FT4 stability test.~~

	<b>Dromedary_C1</b>	<b>Dromedary_C2</b>	<b>Cow_C1</b>	<b>Cow_C2</b>
<b>BFE (mJ)</b>	620 ± 27 <sup>b</sup>	1 018 ± 65 <sup>a</sup>	917 ± 81 <sup>a</sup>	907 ± 68 <sup>a</sup>
<b>SE (mJ.g<sup>-1</sup>)</b>	8.49 ± 0.46 <sup>c</sup>	12.73 ± 0.12 <sup>b</sup>	15.52 ± 0.14 <sup>a</sup>	15.59 ± 0.30 <sup>a</sup>
<b>BD (g.mL<sup>-1</sup>)</b>	0.31 ± 0.00 <sup>a</sup>	0.31 ± 0.00 <sup>b</sup>	0.24 ± 0.00 <sup>d</sup>	0.25 ± 0.00 <sup>c</sup>
<b>CBD at 15 kPa (g.mL<sup>-1</sup>)</b>	0.47 ± 0.00 <sup>b</sup>	0.53 ± 0.00 <sup>a</sup>	0.48 ± 0.01 <sup>b</sup>	0.49 ± 0.01 <sup>b</sup>
<b>Compressibility at 15 kPa (%)</b>	34.2 ± 1.1 <sup>c</sup>	42.6 ± 0.7 <sup>b</sup>	48.8 ± 1.2 <sup>a</sup>	49.1 ± 1.2 <sup>a</sup>
<b>Cohesion (kPa)</b>	4.07 ± 0.13 <sup>b</sup>	4.01 ± 0.35 <sup>b</sup>	5.16 ± 0.05 <sup>a</sup>	5.06 ± 0.36 <sup>a</sup>
<b>FF (-)</b>	1.21 ± 0.04 <sup>a</sup>	1.24 ± 0.11 <sup>a</sup>	1.02 ± 0.02 <sup>b</sup>	1.09 ± 0.06 <sup>ab</sup>

Means with different superscripted letters in the same row were significantly different according to Tukey's HSD test ( $p < 0.05$ ).

**Table 5.** Pearson's correlation coefficients between flow and physicochemical properties.

	<b>Compressibility at 15 kPa (%)</b>	<b>Cohesion (kPa)</b>	<b>FF (-)</b>	<b>BFE (mJ)</b>	<b>SE (mJ.g<sup>-1</sup>)</b>	<b>Fat content (%(w/w) on dry basis)</b>	<b>D<sub>50</sub> (µm)</b>
<b>Compressibility at 15 kPa (%)</b>	-	0.85	-0.77	0.74	0.99	0.80	0.80
<b>Cohesion (kPa)</b>	0.85	-	-0.97	0.28	0.83	0.99	0.88
<b>FF (-)</b>	-0.77	-0.97	-	-0.19	-0.75	-0.97	-0.77
<b>BFE (mJ)</b>	0.74	0.28	-0.19	-	0.76	0.34	0.28
<b>SE (mJ.g<sup>-1</sup>)</b>	0.99	0.83	-0.75	0.76	-	0.86	0.78
<b>Fat content ( %(w/w) on dry basis)</b>	0.88	0.99	-0.97	0.34	0.86	-	0.87
<b>D<sub>50</sub> (µm)</b>	0.80	0.88	-0.76	0.28	0.78	0.87	-