Comparison of the viscosity of camel milk with model milk systems in relation to their atomization properties

Haileeyesus Habtegebriel, Michael Wawire, Volker Gaukel, and Martha L. Taboada

Abstract: To correlate the viscosity of camel milk with its atomization properties, first, the viscosity profiles of camel milk are compared with model milk systems (reconstituted skimmed cow milk powder). Then, atomization experiment was conducted using model milk systems and finally, the findings of the atomization experiments were coincided with the viscosity profiles. The effect of total solids of whole (10% to 40%) and skimmed (7.5% to 30%) camel milks on its viscosity was investigated. At 30% total solids level and a temperature of 20 °C, skimmed camel milk exhibited a viscosity of 7.68 mPa.s whereas whole camel milk 8.96 mPa.s. This value is small compared to suspension of reconstituted skimmed cow milk powder, which reached up to 18.55 mPa.s and to that of suspension of whey protein concentrate (28.15 mPa.s). By raising the total solid from 20% to 30%, it was shown that, the average spray droplet size would be changed from 18.77 to 29.40 μm and the span from 1.76 to 1.55. Based on their viscosity profiles, these values would be obtained for camel milk at total solid values of 35% for whole and 38% for skimmed milks. This would allow camel milk to be concentrated to higher total solid levels than bovine milk.

Keywords: atomization, camel milk, microstructure, particle size, viscosity

Practical Application: Converting camel milk into powder by spray drying will have a great role in its commercialization. To do so, establishing knowledge on the viscosity of camel milk at different total solids levels in relation to its atomization properties would be of paramount importance. Because, this would enable us to fine tune the viscosity of the milk to arrive at a quality powder with all the desired techno-functional properties. Moreover, it will also contribute by furnishing engineering data pertinent to the development, design, or choice of appropriate nozzles for atomization of the milk during spray drying at different drying set ups.

1. INTRODUCTION

Recently, camel milk is getting attention due to its nutritional and medicinal advantages as well as its peculiar inherent properties. Though the gross composition of camel milk vis-à-vis protein, lipids, and total solid content is comparable to cow milk, there are subtle differences on the microstructure of their protein micelles, lipid globules, and protective protein compositions that would make their processing different (Hailu et al., 2016; Khan & Iqbal, 2001; Zouari et al., 2019). Camel milk is reputed for its medicinal advantages and has been used for many years to cure many ailments, including allergens and diabetes (Bornaz, Sahli, Attalah, & Attia, 2009; Farah & Rüegg, 1989, 1991; Konuspayeva, Lemarie, Faye, Gérard, & Didier, 2008). This is mainly associated with its richness in vitamin C (Khan & Iqbal, 2001), protective proteins (immunoglobulins) (Konuspayeva et al., 2008; Levieux, Levieux, El-Hatmi, & Rigaudière, 2006), absence of β-lg, which is the common cause of milk allergies (Hailu et al., 2016) and better fatty acid profiles (the ratio of saturated to unsaturated ones; Konuspayeva et al., 2008).

However, in contrast to cow milk, optimizing the processing of camel milk into commercial dairy products such as cheese, yoghurt, and other type of fermented products has proven to be very difficult (Bornaz et al., 2009; Farah & Rüegg, 1991; Konuspayeva et al., 2008). The curds of the cheese are very soft and the yield is low as proteins escape into the whey (Bornaz et al., 2009). Furthermore, during yoghurt processing, the network of gel formed is unstable and subjected to high level of synersis (Farah & Rüegg, 1991). The variation in colloidal structure (size and size distribution) of casein micelles (Farah & Rüegg, 1989) and lipid globules (Farah & Rüegg, 1991) is presumed to be the major contributor. The differences in the interaction between serum milk proteins and micellar proteins, as a result of the absence of β-lg in camel milk (Levieux et al., 2006), could be the other reason. The presence of a well-established culture of drinking camel milk in the form of tea, coupled with the abovementioned difficulties on processing, makes it encouraging to focus on converting the camel milk into powder. Spray drying is one of the modern technologies employed in drying of milk.

Feed properties, such as viscosity, have to be well investigated to optimize the drying processes. The viscosity of milk can be affected mainly by the total solids level, temperature, and the physical state of the components (lipids and proteins). Several treatments including thermal, mechanical, pH, and aging could alter the physical

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state of milk components (Attaie & Richter, 2000; El-zeini, 2006; Kherouatou, Moncef, & Hamadi, 2003). In industrial practices, the milk is usually concentrated to high total solid levels to get optimal results on the quality of milk powders as well as to save energy (Wittner, Karbstein, & Gaukel, 2019). This in turn would raise the viscosity of the milk.

The viscosity of milk is an important property that influences its atomization during spray drying (Bouchoux et al., 2009; Trinh, Trinh, & Haisman, 2007). The droplet size produced during atomization is of upmost importance for the resulting powder. Too large drops may lead to an incomplete drying at the same time resulting, for example, in stickiness and reduced storage stability (Yoganandi, Mehta, Wadhwani, Darji, & Aparnathi, 2014) while too small drops can lead to thermal degradation reactions within the fine fraction (Schröder, Kraus, Rocha, Gaukel, & Schuchmann, 2011) or to the formation of undesired fine particles (Finotello et al., 2018).

In addition to the physical properties of the liquid (viscosity, surface tension, density, concentration, etc.), the type of nozzle and its process parameters (Stähle, Schuchmann, & Gaukel, 2015) can affect the drop size and size distribution. Pressure-swirl nozzles are popular in many milk powder manufacturing industries due to their economic advantage and suitability (Lefebvre & McDonell, 2017). As the name implies, the working principle of pressure-swirl atomizers relies on applying pressure and generating a swirl flow to convert the potential energy of the liquid into kinetic energy, which results in relative velocity differences thus generating between the spray stream and the air outside. Mechanistically explained, the liquid enters the swirl chamber tangentially and forms an air core inside the nozzle due to the swirling motion. An annular liquid lamella is formed, which eventually disintegrates due to internal instabilities as well as due to instabilities originating from the interplay between the fast moving liquid sheet with the surrounding air (Lefebvre & Wang, 1987).

Factors coming from the milk (such as viscosity, density, and surface tension) as well as from atomizer operating conditions and atomization mechanisms (type of atomizer) are hence the most important factors that control the droplet sizes. The optimization of the spray drying process is on the other hand highly dependent on the formation of desirable droplets. Though there is a wide range of research reports on the evolution of the viscosity of cow milk under different processing environments, there is a gap on similar information for camel milk. Most of the information available on camel milk is on its physicochemical properties. No work is reported on the effect of total solid levels on its viscosity. This makes it difficult to predict its atomization properties. The current study is designed to abridge this gap.To correlate the viscosity of camel milk with its atomization properties, first the viscosity of the milk is studied at different fat and total solid levels and this is compared with model milk systems. Then, a second set of experiment was conducted to correlate the viscosity of the milk systems with atomization process using model milk systems. Finally, the findings on the atomization experiments were translated to that of camel milk by coinciding the viscosity profiles of camel milk with the model milk systems.

2. MATERIALS AND METHODS

2.1 Materials

Materials used are camel milk, camel milk powder, model milk systems (skimmed milk powder, whey protein concentrate and lactose).

2.2 Origin of camel milk

Fresh whole camel milk was supplied by Dutch Oasis camel milk, the Netherlands. The gross compositions were done by the company and accordingly, the whole camel milk contains 10.26% total solid out of which, 2.72% is protein, 3.36% fat, 3.44% lactose, and 0.72% salt.

2.3 Viscosity

A rheometers (Physica MCR 101/301, Anton Paar, Graz, Austria) with a double gap geometry (DG26.7) were employed for viscosity measurements. The measurements were performed at 20 °C with a logarithmic shear rate controlled ramp in the range of 1 to 1,000 s^{-1}.

2.4 Particle size

The particle sizes of casein micelles and fat globules of camel milk were measured using a laser diffraction spectroscope from Retsch Technology (HORIBA LA950, Retsch Technology GmbH, Haan, Germany). The refractive indexes of camel milk, 1.4490 (Berhe, Seifu, & Kurtu, 2013) with $i = 0$ and 1.333 for the continuous phase were considered. Demineralized water was used throughout the experiments.

2.5 Atomization test rig

For the atomization experiments, a spray test rig (Spraytec, Malvern, Herrenberg, Germany) was used. Prior to atomization, the solutions were tempered to 20 °C in a jacketed vessel. An air driven piston pump (Wilhelm Böllhoff GmbH & Co., Bielefeld, Germany) was used to supply the solutions through a pressure-swirl atomizer with an orifice diameter of 0.3 mm and a cone angle of 60° (type 121, Schlick-Düsen GmbH, Germany). To avoid blockage of the exit orifice, the nozzle is equipped with a suitable filter. Atomization was performed at a constant pressure of 100 bar. The corresponding flow rate was measured with a flow meter (VSE0,04/16, VSE GmbH, Germany). To measure the spray droplet size, a laser diffraction spectroscope with a 750-mm focal lens (Malvern Instrument, Malvern, UK) was mounted to the test rig and placed 25 cm underneath the nozzle orifice, perpendicular to the spray cone axis. For the measurements, the data acquisition rate was set to 250 Hz over a time of 25 s, which resulted in 6,250 recorded droplet size distributions, from which an averaged distribution is calculated. From these data, the spray sauter mean diameter was calculated at each viscosity. The measurements were executed in triplicate and the suspensions were prepared in duplicate giving rise to six measurements at each viscosity value.

2.6 Preparation of suspensions of skim milk powder, whey protein concentrate, and lactose

For particle size and viscosity measurements, a calculated amount of low-heat skimmed milk powder (OMIRA GmbH, Ravensburg, Germany) or whey protein concentrates of 80% (w/w) protein and 94% (w/w) total solids content (Nutri Whey 800F, Friesland Campina, the Netherlands) were reconstituted in a beaker using demineralized water by stirring with a magnetic stirrer at room temperature for over 3 hr. The reconstituted suspensions were refrigerated (4 °C) and stored overnight for complete rehydration. Prior to the measurements, the samples were conditioned to room temperature. For lactose, a crystalline lactose powder (Alpavit, Lauben/Allgäu, Germany) was mixed with demineralized water, stirred at 350 rev/min at 60 °C for an hour until a clear, colorless solution was obtained. For the atomization experiment, a calculated amount of skim milk powder, and distilled

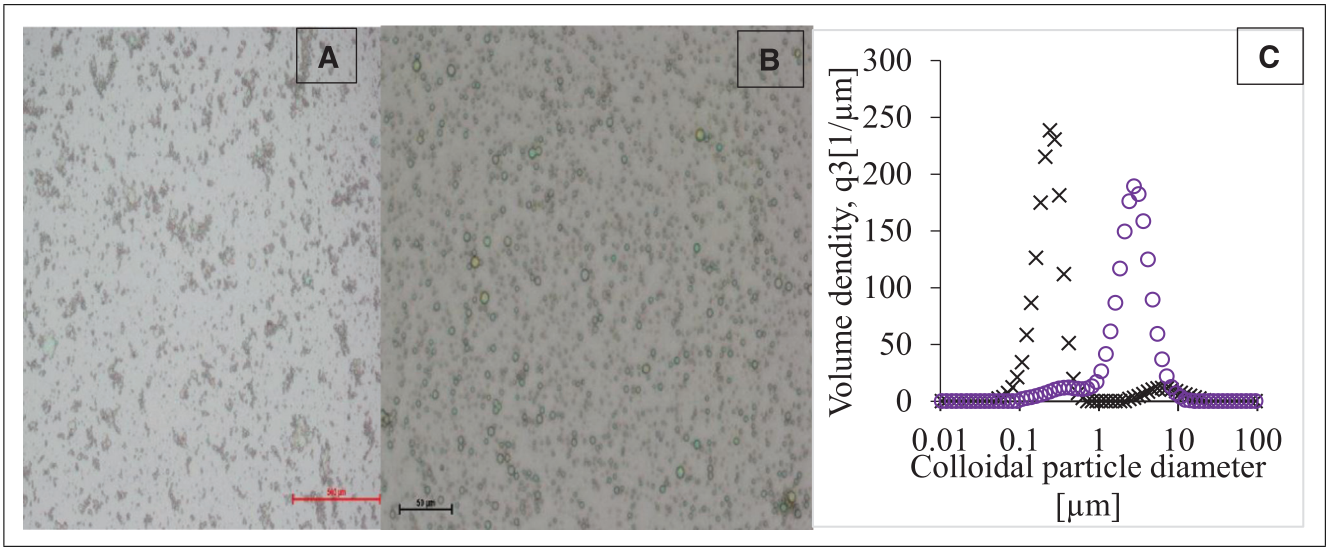

Figure 1–The microstructure of fat globules and size and size distribution of camel milk fat globules and casein micelles: (A) camel milk fat globules, 10× magnification; (B) camel milk fat globules, 20× magnification; (C) particle size and size distribution of camel milk (cross mark = skimmed camel milk; circle mark = whole camel milk).

water were mixed in a bucket and stirred using an overhead stirrer at 750 rev/min for 3 hr until complete dissolution occurs.

2.7 Microscope

Camel milk fat globular structure was examined by the microscope (Eclipse LV100ND; Nikon, Japan) equipped with a digital camera. Milk or cream samples were spread between slide and cover glass and observed under a transmitted light microscope.

2.8 Skimming

The fat content of the camel milk was removed by centrifugation at 4 °C and 5,000 × *g* for 10 min on a centrifuge (Eppendorf 5430 R, Hamburg, Germany). The cream was removed from the centrifuge cups using a spatula.

2.9 Concentration

Whole and skimmed camel milks were concentrated using a vacuum evaporator (Heidolph Laborota 4000, Heidolph instruments GmBH, Germany). The temperature was adjusted to 55 °C and the vacuum pressure to 120 mbar.

2.10 Total solids

The total solid level is determined by measuring the weight loss after drying the sample in an oven at 85 °C for 3 days.

3. RESULTS AND DISCUSSION

3.1 Camel milk microstructure, colloidal particle size, and size distributions

The microstructure of camel milk fat globules was investigated under light microscope. As can be seen on Figure 1, just like bovine milk, camel milk fat constitutes a discontinuous dispersed phase composed of spherical globules with a wide size distribution. Figure 1 depicts that the camel milk dispersed phase is composed of fat globules of variable sizes (see Figure 1b, bigger globules as indicated in arrows and smaller ones encircled). Other studies also made similar observations in that both fresh camel and bovine milk fat globules observed under optical light transmitted microscope, exhibited similar dispersed phase of fat made of spherical droplets (Attia, Kherouatou, Fakhfakh, Khorchani, & Trigui, 2000). Attia et al., 2000) also indicated that compared to cow milk fat, camel milk fat globules exhibited higher amount of smaller diameter globules, which could be associated with its difficulty in processing (e.g., churning).

The colloidal size and size distribution of camel milk fat globules and casein micelles are presented in Figure 1c, whereby the relative colloidal size distribution of fat globules and casein micelles both in whole and skimmed camel milks are presented side by side, respectively, so that one can infer which peak belongs to the casein micelles and which one to the fat globules. It illustrates that the normalized volume density distribution of the particles in skimmed camel milk exhibited two modes, one smaller and the other larger. Similarly, the whole milk exhibits two modes. When the two curves are superimposed (Figure 1c), it will locate the modes belonging to casein micelles and fat globules of camel milk. Here, in the second curve, that is, in whole camel milk, the larger mode belongs to fat globules and the second weaker mode to the left belongs to casein micelles. Whereas, when the fats are removed (in the case of skimmed camel milk), the weaker mode gets stronger and indicates the location of size of casein micelles in the system.

Compared to that of casein micelle distribution of milk of other animal species, the values for camel milk lie on similar range. For example, Attaie and Richter (2000) demonstrated that the cumulative frequency distribution of casein micelles of bovine and goat milk serum, studied under light microscope, was in the range of less or equal to 0.13 µm (both) for 10% of the population, 0.23 and 0.25 µm for 50% of the population, 0.46 and 0.47 µm for the 90% of the population, and sauter mean diameters of 0.213 and 0.223 µm, respectively, for cow and goat milks. All these values are in a similar range as those observed in this study. Only a slight difference on the values at 90% was observed, for which, camel milk, with a value of 0.41 µm, was found to be less than that of goat and cow milk (see Table 1).

There are also some studies which reported different values. For camel milk, studied under electron microscopy, the sauter mean diameter of casein micelles ranged from 0.113 to 0.165 µm (Farah & Rüegg, 1989). The differences obtained here could be due to the

Table 1–The parameters of colloidal particle size and size distribution for skimmed and whole camel milk.

	Data from present study For camel milk		Data from Attaie and Richter (2000)			
			For goat milk		For bovine milk	
Size parameter	SCM	WCM	SGM	WGM	SBM	WBM
×10.3 (µm)	0.14	1.10	0.13	1.69	0.13	2.23
×50.3 (µm)	0.24	2.68	0.25	3.09	0.23	3.84
×90.3 (µm)	0.41	4.91	0.47	5.21	0.46	6.42
×3.2 (Sauter mean diameter) (µm)	0.22	1.65				
Span	1.15	1.43				

Note. S refers to skimmed, W to whole, CM to Camel Milk, GM to goat milk and BM to bovine milk.

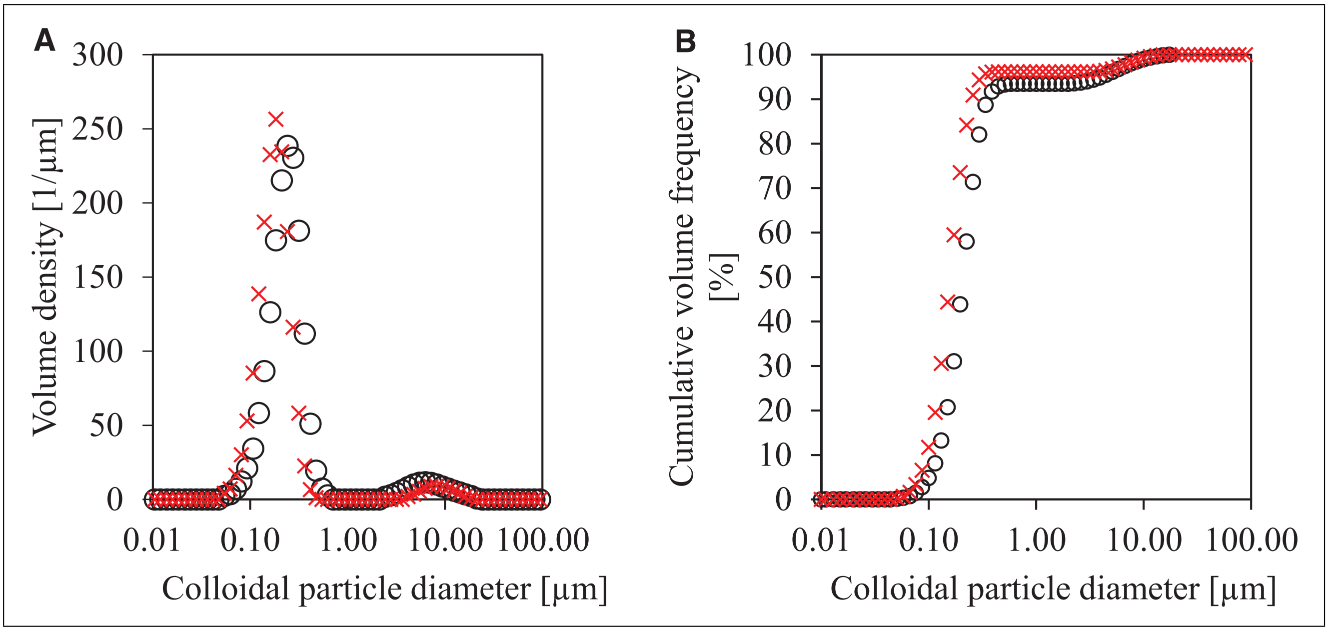

Figure 2–Comparison of the colloidal particle size and size distribution of skimmed camel milk (SCM, circle marks) with suspension of skimmed cow milk powder (SMP, cross marks): (A) volume density distribution, (B) cumulative volume frequency.

methodologies employed. In this case, laser diffraction technique was used. Regarding the colloidal size distribution of fat globules, the particle sizes ranged from 0.94 to 8.24 µm with a mode at 2.78 µm. The sauter mean diameter was 1.65 µm, whereas the 50% population exhibited a size less than 2.68 µm and the 90% less than 4.91 µm (see Table 1). Farah and Rüegg (1991) reported that camel milk fat globules exhibited a mean diameter of 2.61 µm. Attia et al. (2000) also indicated that about 55% of the population exhibited volume averaged diameter of less or equal to 2 µm. It was also observed that the diameter of most camel milk fat globules lie in the range of 2 to 4 µm, which represent the 61% of the population (El-zeini, 2006).

3.2 Colloidal particle size and size distribution of skimmed camel milk vis-à-vis suspension of skimmed cow milk powder

Figure 2 illustrates the difference in colloidal particle size of skimmed camel milk and suspension of skimmed cow milk powder. Globally, both liquids show a similar distribution, however skimmed camel showed a slightly greater particles size. The 90% of the population is under a diameter of 0.34 µm for skimmed camel milk, whereas it is under 0.26 µm for suspension of skimmed cow milk powder. Similar results were reported by other studies in that the micellar size of camel milk is greater than that of skimmed bovine milk (Kamal, Foukani, & Karoui, 2017; Kherouatou et al., 2003). Bornaz et al. (2009) indicated that the micellar diameter for camel milk ranged from 280 to 550 nm, which is a wider distribution than that of all other species they compared (cow, goat, ewes) (Bornaz et al., 2009). Kamal et al. (2017) also compared the casein micellar size distribution of camel milk with that of bovine casein micelles and found that camel caseins exhibited greater size as well as size distribution than bovine milk with a modal diameter values of 468 nm for camel milk casein micelles and 137 nm for cow milk. For suspension of skimmed cow milk powder, on the other hand, the micelle diameter is in the range of 50 to 480 nm, which is in agreement with other studies, in which it is found to vary from 50 to 500 nm (Bouchoux et al., 2009). The skimmed cow milk powder in our experiment is dissolved in demineralized water, which could be somehow a different environment than the native milk system, and this could contribute to a difference in size of the micelles. Moreover, the casein micelles in skimmed cow milk powder could be changed due to the mechanical and thermal treatments they were subjected to, during drying. Thus, the similarity in the micellar size and size distribution of cow and camel milks would indicate that differences in the physicochemical properties of the two milks (such as

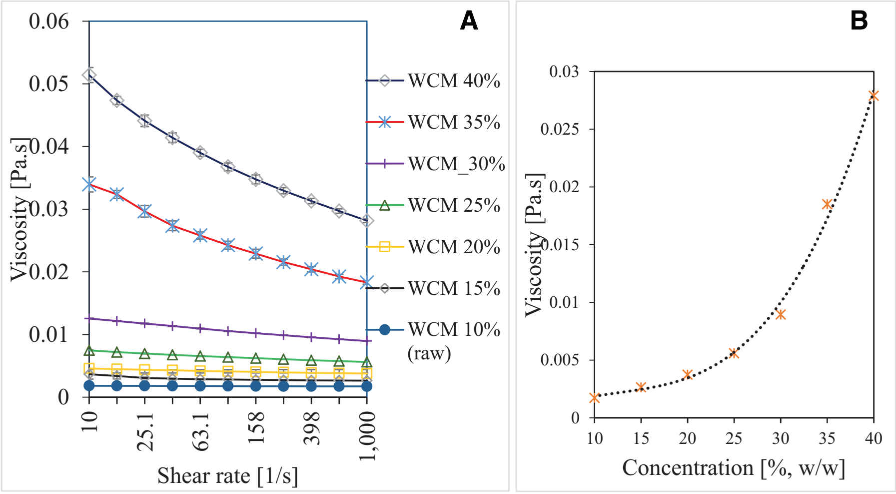

Figure 3–The change in viscosity of whole camel milk with varying levels of (A) shear rate and (B) total solid levels (the viscosity values here are taken at the highest shear rate).
Note. WCM refers to whole camel milk followed by the total solid levels. Mean values are represented by markers and standard deviation by error bars (the standard deviations at lower concentration are near to zero). Marker symbols in Figure 3b represent experimental values, and the line corresponds to fitting of the cubic curve.

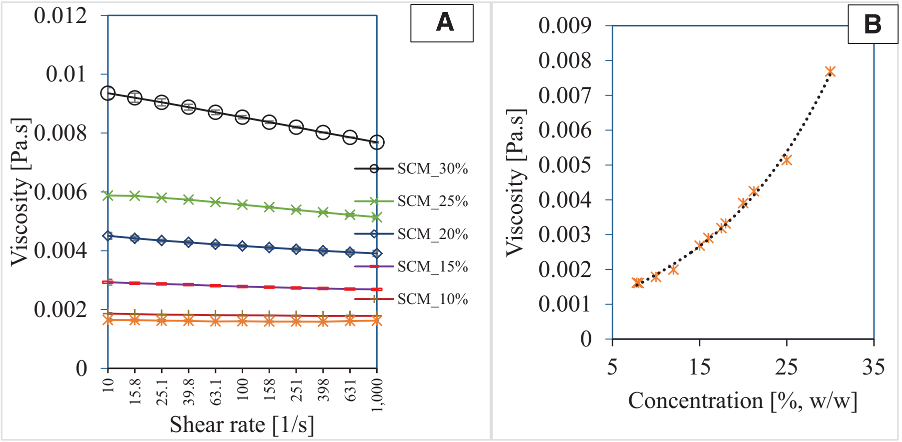

Figure 4–The change in viscosity of skimmed camel milk with (A) shear rate and (B) total solid levels (the viscosity values here are taken at the highest shear rate). SCM refers to skimmed camel milk followed by the total solid levels. Marker symbols in Figure 4b represent experimental values, and the line corresponds to fitting of the cubic curve.

viscosities) would better be explained in terms of factors other than size of particles (such as interaction among colloidal micellar proteins and soluble whey proteins).

3.3 Effect of concentration on the viscosity of whole and skimmed camel milk

As can be seen from Figure 3a, the viscosity of whole camel milk, as taken from the highest possible shear rate, behaves as a Newtonian fluid for concentrations up to 25% (w/w). The fitted curve of the data points is presented alongside to guide the eye. A slight shear thinning behavior starts to develop from a concentration of 30% (w/w) and grows rapidly then after. The reason could be that, in milk systems, an increased shear rate deforms or rearranges particles, resulting in a lower flow resistance (Bouchoux et al., 2009; Finotello et al., 2018). Similar pattern was recognized in other studies conducted on cow milk. In reconstituted whole cow milk powder, a Newtonian behavior was observed at concentrations up to 30% (w/w) total solids and a shear thinning behavior above it (Trinh et al., 2007). However, different total solid levels were also compiled, ranging from 15% to 25% TS (% w/w), for the transition from Newtonian to non-Newtonian regimes depending on the composition and heat treatment of cow milk systems (Finotello et al., 2018). These variations on the threshold for shear thinning properties could be associated to the difference in the treatments the milk systems are subjected to. The viscosity of camel milk at 10% (w/w) total solid (comparable to concentration to average whole camel milk) was 1.73 mPa.s. This value is in agreement with other values reported elsewhere (Yoganandi et al., 2014). Yoganandi et al. 2014, for example, reported that whole camel milk exhibited a viscosity of 1.77 mPa.s at 20 °C and total solid level of 12.74%.

For fresh skimmed camel milk, the viscosity is found to be 1.60 mPa.s at a total solid value of 7.6% and 1.78 mPa.s at 10% (w/w). This is comparable with the value of suspension of skimmed cow milk powder, 1.60 mPa.s (see Figure 4a). For concentrated skimmed camel milk, the viscosity is predominated by Newtonian behavior for concentration up to 25% (w/w) total solids. Only a slight shear thinning behavior is exhibited at a concentration of 30%. Similarly, the suspension of skimmed cow milk powder exhibited a shear thinning behavior at concentrations greater than 30% (see Figure 5a). An increasing trend of viscosity of skimmed cow milk with concentration is demonstrated elsewhere (Fernández-Martín, 2009). Morison, Phelan, and Bloore (2013) also reported that, at concentrations up to 20% total solids, skim milk concentrate was Newtonian, but above 30% concentration, it exhibited pseudoplastic (shear thinning) behavior.

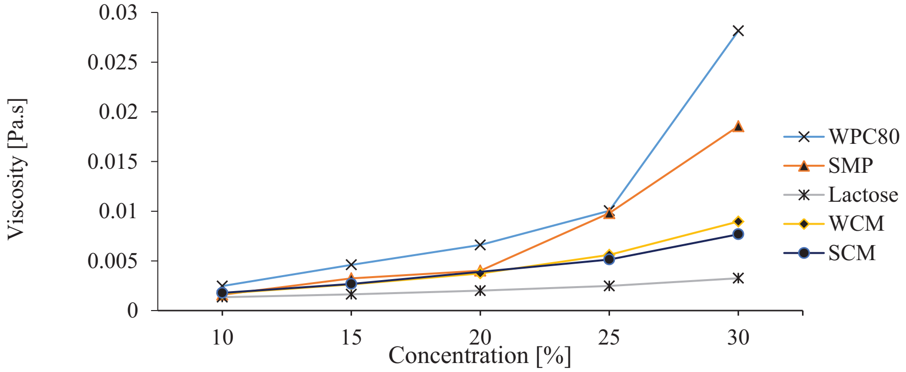

Figure 5–The change in viscosity of camel milk and model milk systems with concentration.
Note. SCM, skimmed camel milk; WCM, whole camel milk; SMP, suspension of skimmed cow milk powder; WPC80, suspension of whey protein concentrate.

Table 2–The composition of camel milk with regard to lactose and β-lg as reported in the literature.

	Reported values of lactose in camel milk			Reports on the absence of β-lg In camel milk	
References	Lactose	Total solids (TS)	% TS On dry basis	References	β-lg
(Farah & Rüegg, 1989)	5.24	12.2	42.95	(El-Agamy et al., 2009)	-
(Guliye et al., 2000)	4.81	11.5	41.82	(Laleye et al., 2008)	-
(Attia et al., 2000)	5.4	9.61	56.19	(Al haj & Al Kanhal, 2010)	-
(Omer & Eltinay, 2009)	4.41	9.78	45.09	(Farah & Atkins, 1991)	-

Furthermore, skimmed cow milk concentrated to 45% total solids exhibited shear thinning behavior, showing higher apparent viscosities at lower shear rates that drops rapidly with shear rate up to 200 s^{-1} (Bienvenue, Jiménez-Flores, & Singh, 2003).

3.4 Comparison of the viscosity of camel milk systems with that of suspensions of model milk systems

In order to figure out the effect of the absence of β-lg and the relative abundance of lactose in camel milk on its viscosity, as shown in Table 2, the viscosity of whole and skimmed camel milks at different concentrations was put in a context of whey protein–dominant and lactose-dominant situations (Figure 5). As expected, the suspensions of whey protein concentrate (WPC80) exhibited higher viscosity than all of the suspensions including camel milk at the investigated concentrations range. This is because, as WPC80 contains higher amounts of globular whey proteins such as β-lg, stronger interactive forces would be formed among themselves (whey proteins) leading to an overall increase in the viscosity of the system. On the other hand, camel milk exhibited similar viscosity with skimmed milk system up to a concentration of 20% (w/w). After a concentration of 25% however, the viscosity of suspensions of skimmed cow milk powder starts to rise faster than that of camel milk systems. This might be explained in terms of the interactive role of whey proteins with casein micelles. Globular proteins in milk, such as β-lg, play an important role in increasing viscosity of milk as a result of its interactive role with other milk proteins (caseins) (Morison et al., 2013). There are lots of research evidences demonstrating that camel milk has no (or negligible amount of) β-lg (Farah & Atkins, 1991; Hailu et al., 2016). So, due to lack of this whey protein, the caseins might interact weakly with each other at higher concentrations, resulting in less resistance to shearing forces. This might also be the reason for the thin consistency of yoghurt and fermented dairy products made of camel milk (Farah & Rüegg, 1991). Based on the size and size distribution profiles, skimmed camel milk exhibited greater (or similar) micellar sizes than suspension of the skimmed cow milk powder (compared under similar experimental set up). This suggests that the viscosities of the two milks (cow and camel) as a result of size exclusion effect of the micellar structures should have been in the same range. However, significant difference is observed at higher concentrations (above 25%). So, factors other than the size exclusion effects should be attributable to the observed gap in the viscosity values. The differences in interaction between the globular whey proteins (such as β-lg) with casein micelles might bear one of the reasons for the observed difference. As opposed to cow milk, the absence of β-lg in camel milk thus could be one of the factors for the lower viscosity of camel milk.

3.5 Effect of the viscosity of suspension of skimmed cow milk powder on the droplet size and size distribution during atomization

To understand the effect of viscosity of milk on the drop size and size distribution, skimmed cow milk was dissolved at different concentrations and spray test was conducted. Then, the corresponding viscosities for camel milk were determined from the previous viscosity studies. The result indicated that the drop size and size distribution of generated droplets changed with the viscosity of the milk at above a certain limit, ≥4 mPa.s. As indicated in Figure 6, higher drop sizes were obtained at 30% total solids level and there was no statistically significant difference in droplet sizes and span for 20% and 10% total solid levels.

As pointed out in Table 3, the suspension of skim milk powder at a viscosity of 18.55 mPa.s (30% TS, w/w) had greater normalized average volumetric diameter in all droplet distribution size classes of the population than its 20% and 10% counterparts. The 10% of the population in the cumulative frequency curve (Figure 6) had an average size of less or equal to 15.56 μm, 9.07 μm, and 8.84 μm, whereas the 50% had less or equal to 44.87; 30.80 and 30.72 μm and the 90% of the population had a diameter less or equal to 84.84, 63.35, and 65.60 μm, respectively, at 30%, 20%, and 10% total solid levels. The other important spray parameter investigated was the span of the size distributions. From spray drying

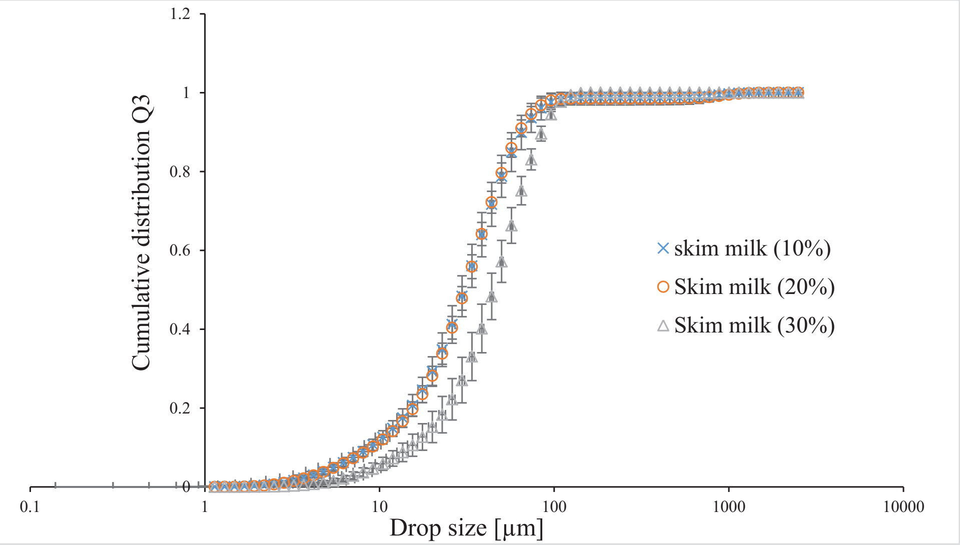

Figure 6–The cumulative distribution curves for drop size distribution of skim milk suspensions at different viscosity values (Schlick nozzle).

Table 3–Process parameters for the atomization experiment and the corresponding droplet size and size distribution profiles.

	Concentration (%w/w)		
Parameter	**30**	**20**	**10**
Viscosity (mPa.s) at shear rate of 1000 s^{-1}	18.55	4.02	1.59
Average flow rate (L/min)	0.24 ± 0.014	0.18 ± 0.004	0.16 ± 0.000
Atomization pressure (bar)	100	100	100
Atomization temperature (°C)	20.40 ± 0.14	20.43 ± 0.09	20.60 ± 0.54
Average drop size (µm)	29.40 ± 4.12	18.77 ± 1.27	18.44 ± 1.53
Span	1.55 ± 0.16	1.76 ± 0.10	1.84 ± 0.10
×10.3 (µm)**	15.56 ± 2.96	9.07 ± 0.86	8.84 ± 0.84
×50.3 (µm)**	44.87 ± 3.83	30.80 ± 1.60	30.72 ± 2.81
×90.3 (µm)**	84.84 ± 3.88	63.35 ± 3.85	65.60 ± 8.77
t-ratio		0.0008*	0.3600

*Significant at 5% significance level (comparison between the average drop size for 30% and 20%).
**×10.3, ×50.3, and ×90.3 refers to the diameter less or equal to which 10%, 50%, and 90% of the population, respectively, are represented by.

point of view, this is an important aspect as it lets us produce powders of desired properties with better uniformity (Schröder et al., 2011). When the drop size becomes less uniform (higher span), it results in excessive heat damage to finer droplets by the time bigger drops are drying optimally resulting in the nonuniformity of the product (Schröder et al., 2011). In this study, it is observed that, the smallest value of span (1.55) was found for 30% total solid levels as opposed to 1.76 and 1.84 for 20% and 10% total solid levels, respectively (5% significance level). This indicates that droplet sizes of better uniformity and desirable sizes, at this given experimental set up, could be obtained by fine tuning the viscosity at around the non-Newtonian regime (viscosity of 18.22 mPa.s). Similar results were found in studies conducted on different fluids. For example, Stähle et al. (2015) showed that bigger drops of spray were formed at higher viscosities in a maltodextrin solution.

On the other hand, it was shown that the sauter mean diameter of biofuel sprays increased with viscosity in pressure-swirl atomizers (Lefebvre & Wang, 1987). The reason could be better explained in terms of the mechanism of spray formation in the type of nozzle used. In this type of atomizer design, a conical sheet of liquid is formed inside the swirl chamber as a result of the tangential introduction of the liquid (Stähle et al., 2015). As this sheet leaves the nozzle orifice, it disintegrates into ligaments and then into droplets of several sizes as modulated by the interplay between several forces acting on it, namely, aerodynamic forces, viscous forces, surface tension forces, and internal dynamic stresses forces (Lefebvre & McDonell, 2017). When the viscosity is too low, the internal instabilities (turbulent forces) will govern the drop break down and as a result finer droplets will be formed. But at higher viscosities, the liquid flow rate will be increased (see also Table 3), resulting in thicker films (Rizk & Lefebvre, 1980) and in which case, viscous forces will also be important and tend to damp disintegration of the sheets into ligaments and then into drops, leading to the formation of bigger drops (Lefebvre & McDonell, 2017; Rizk & Lefebvre, 1980; Stähle et al., 2015).

As it is already observed from the viscosity and concentration curves above, the linear relation between viscosity and concentration vanishes at a concentration above 25% for suspension of skimmed milk powder and above 30% for skimmed camel milk. The Newtonian regime of the fluids will be more dominant at these concentrations. Hence, for concentrations up to this value, fluid instabilities arising from turbulent forces could be important in drop formation process. But, above these points, interactive forces come to play a role in determining the viscosity of the liquid (as shown by forming shear thinning behavior), making viscous forces more important in drop formation mechanism. Accordingly, change in drop size during atomization could be detected at those viscosity levels, and which will be at 30% total solid level for suspension of skimmed milk powder. By referring to the viscosity curve that belongs to the corresponding viscosity of 18.55 mPa.s, it is found that a drop size of 29.4 µm could be achieved only if the concentration of whole camel milk is raised to 35% and, by deducting the effect of fat, that of skimmed camel milk would need to be raised to 38%. This could be considered as an advantage in industrial processing where the objective is to spray milk with the maximum possible concentration without the impediment of the flow. Thus, camel milk could be concentrated to greater concentrations than cow milk to get drops of similar atomization properties without affecting the flow.

4. CONCLUSIONS

The microstructure of camel milk fat globules exhibited similar spherical shapes with that of cow milk fat phase. The micellar size and size distribution of camel milk is in the same range with that of reconstituted skimmed milk powder, with slight greater diameters for skimmed camel milk. The viscosity of skimmed camel milk is in the same range with that of reconstituted skimmed cow milk powders at lower concentrations and becomes lesser with increasing higher concentrations. Size and size distribution studies indicated that factors other than particle sizes (such as interactive forces among whey and casein proteins) should be responsible for the lower viscosity of skimmed camel milk than cow milk. It is shown that the droplet size of milk sprays could be fine-tuned only after a concentration limit of 20% (the onset of the non-Newtonian regime). Larger droplets with narrower span could be obtained at total solid level of 30% using pressure-swirl nozzle (Schlick type) and operating at 100 bar of atomization pressure and a temperature of 20 °C. Due to its low viscosity as compared to the cow milk, atomization at higher total solids would be more convenient for camel milk. This makes it advantageous for the spray drying process (less water to evaporate)

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AUTHOR CONTRIBUTIONS

Haileeyesus Habtegebriel designed the study, collected test data, interpreted the results, and drafted and revised the article. Volker Gaukel designed the study, interpreted the results, and drafted and revised the article. Michael Wawire designed the study, interpreted the results, and drafted and revised the article. Taboada Martha designed the study, interpreted the results, and drafted and revised the article.

CONFLICTS OF INTEREST

There is no conflicts of interest to acknowledge.

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