



Research paper

Surface characteristics and rehydration behavior of sodium caseinate powder obtained from camel and bovine milks

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ABSTRACT

This study investigated the surface characteristics and the rehydration behavior of sodium caseinate powder obtained from camel and bovine milk (CMSCP, BMSCP, respectively). Both powders exhibited similar total fat and ash contents, whereas CMSCP contained slightly lower protein and higher lactose quantity than BMSCP. Despite having comparable fat content, the X-ray photoelectron spectroscopy indicated that CMSCP exhibited greater surface fat ($48.9 \pm 2.4\%$) and lower protein ($50.4 \pm 2.5\%$) contents than BMSCP. This highlighted the hydrophobic nature of CMSCP surface which was confirmed by its higher C/O ratio (5.6 ± 0.3). FT-IR spectroscopy confirmed the structural differences between both powders. CMSCP displayed strong hydrophobic protein-protein interaction and a higher β -sheet structure, as well as a unique glycerol-casein band at 1037 cm^{-1} , indicating the development of insoluble aggregates. Such protein aggregations, surface fat coverage and surface hydrophobicity deeply reduced the rehydration behavior of CMSCP which was confirmed by the turbidity measurements.

1. Introduction

Sodium caseinate powder is a valuable ingredient in many food formulations. Indeed, caseins present many techno-functional properties which improve the foaming, emulsifying and gelling behaviors (Loi et al., 2020; Marafon et al., 2011; Martínez-Padilla et al., 2014). Sodium caseinate powder is usually produced by spray-drying. This technique is suitable to increase the shelf-life of dairy liquids without altering their functionalities.

During spray drying, water is evaporated from dairy liquid droplets following a brief period of contact with dried hot air. The resulting powders present important advantages regarding the handling, storage and transport. These advantages are more likely to be associated with the surface characteristics of the powder. It is well known that the surface composition of milk powders affects their functional properties such as the stickiness, the wettability, and the flowability (Murrieta-Pazos et al., 2012a; Nijdam & Langrish, 2006). The surface composition of milk powders has been extensively studied using the X-ray photoelectron spectroscopy (XPS). The XPS is described as a well-established technique that determines the elementary composition

(i.e. carbon, oxygen, and nitrogen) and their subsequent functions (e.g. C-C (H), C-O, C=O, O-C=O etc.) within a powder surface thickness of 5 to 10 nm. The resulting composition are converted into proteins, fats, and lactose surface content following a matrix detailed by Fäldt & Bergensstahl (1994). The use of XPS spectroscopy was crucial to understand the migration mechanism of milk component (mainly proteins, fats and lactose) to the dried particle surface (Gaiani et al., 2006; Kim et al., 2002; Shrestha et al., 2007; Zouari et al., 2020a). Analysis of these studies highlighted the over-exposure of fat (followed by proteins) at the surface even for skimmed milk powder whatever the milk species origin or the dryer scale (laboratory, pilot or industrial). Lactose is usually located in the inner part of the powder particle and mostly covered by proteins (casein micelles or whey proteins) (Murrieta-Pazos et al., 2012a; Zouari et al., 2020b). It is important to notice that, contrary to lactose and protein, increasing the fat content and/or the drying temperatures have led to the increase of surface fat coverage of milk powder particles (Gaiani et al., 2010; Nijdam & Langrish, 2006). Likewise, changing the composition and/or size distribution of milk fat directly impacts their exposure to the surface (Vignolles et al., 2009; Zouari et al., 2020a). Besides, the XPS spectroscopy was also used to follow up

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dairy powder surface composition during storage (up to 60 days at 20 and 50 °C) (Gaiani et al., 2007 a). Depending on the storage container, the surface composition starts to change after 30 days. These changes are mainly related to lactose crystallization (if storage temperature or relative humidity are not controlled) (Qi et al., 2026) and/or fat migration to the surface (Kim et al., 2009).

Within the last few decades, an important need to develop innovative dairy-based ingredients has been requested by the food industry. Currently, bovine milk and milk derivatives are the most consumed and processed milk. Nevertheless, other milks such as camel milk are the principal dairy resource in many arid and semi-arid regions (Al Haj & Al Kanhal, 2010). Many researchers have investigated the composition of camel milk in comparison with that of bovine milk (Al Haj & Al Kanhal, 2010; Desouky et al., 2013; Konuspayeva et al., 2009). When compared to bovine milk, the caseins of camel milk are composed of higher β -casein (47%), lower κ -casein (3.5%) and similar α -casein (34 %) contents (Zouari et al., 2018). These differences could be a critical parameter for the production of camel milk sodium caseinate powder and may impact its functionality (e.g. rehydration properties).

One of the most challenging steps after powder production is its rehydration ability. Indeed, the rehydration properties are among the most essential quality attributes of a dairy powder (Hussain et al., 2012). A number of actors in the industry pointed out some problems associated with the different steps of the rehydration process: wettability, dispersibility, and solubility. Several researchers used turbidity sensors in dairy research to study rehydration stages. The turbidity profiles are promising tools to appraise milk powder rehydration parameters and to determine the influencing factors on the rehydration process (Felix da Silva et al., 2018; Roy & Amamcharla, 2025). The experiments reported showed clearly that rehydration duration, the incorporation mode, the mixing parameters, the milk concentration, the granulation and the physical state of the powder, the powder surface characteristics as well as its composition were of paramount importance (Gaiani et al., 2007 b; McSweeney et al., 2020). Indeed, turbidity probes were employed to investigate the rehydration of agglomerated and non-agglomerated micellar casein powders, as well as dairy powder (Gaiani et al., 2005, 2009). Measuring the backscattering turbidity profiles enabled the wetting, swelling, dispersion and dissolution stages to be elucidated. In addition, Hussain et al. (2011) observed that adding high NaCl concentrations (0.06–0.12 g/L, w/v) to water enhanced whey protein isolate powder swelling, leading to faster turbidity stabilization. Recently, Sadat et al. (2017) studied the solubility of milk powders containing disodium phosphate and tetrasodium pyrophosphate mixtures. They observed a decrease in the turbidity of reconstituted milk powders, both with and without the addition of disodium and/or tetrasodium pyrophosphate. This decrease was attributed to the difference in refractive index between the serum phase and the casein particles during dissolution. Orlien et al. (2010) used turbidity to investigate the impact of pressure, pH, and rehydration temperature on the reconstitution process of skimmed milk powder. They underlined that high-pressure treatment decreased the turbidity of reconstituted milk powders regardless of the pH or temperature used. This effect was related to casein micelle dissociation under high pressure.

To the best knowledge of the authors, only a few studies have been dedicated to researching the surface of camel milk powder (Zouari et al., 2020a) and its rehydration ability (Abu-Lehia, 1998). However, none of these studies have evaluated the characteristics of camel milk sodium caseinate powder (CMSCP). Thus, the overall aim of this study was to understand the rehydration behavior of camel milk sodium caseinate powder combining several technics. First of all, the bulk and the surface composition, of CMSCP were studied. Then the rehydration process of CMSCP was assessed using continuous turbidity based on generated backscattering profiles. To create a well based comparative study, bovine milk sodium caseinate powders (BMSCP) were produced under the same drying conditions and were evaluated following the same characterization techniques.

2. Materials and methods

2.1. Sodium caseinate preparation

Firstly, camel and bovine milks were firstly acidified with HCL 0.1M. The obtained pellet after acidification was essentially composed of caseins. This pellet was, then, diluted in ultrapure water in equivalent quantity to the recovered acid whey. The pH was gradually adjusted to the initial pH of bovine or camel milk using a NaOH 1M solution. The obtained camel and bovine sodium caseinates were subsequently microbiologically stabilized by the addition of 2.10^{-4} g/ml of sodium azide.

2.2. Sodium caseinate powder production

Samples of camel and bovine sodium caseinate were spray-dried using a Büchi mini spray dryer (model B-290, Büchi Labortechnik AG, Flawil, Switzerland). The inlet and outlet drying temperatures were set to 200 ± 2 °C and 80 ± 2 °C, respectively. During drying, the absolute humidity of the air was 5 g of water per kg of dry air (determined using Mollier Diagram). The obtained powders are CMSCP: Camel milk sodium caseinate powder and BMSCP: Bovine milk sodium caseinate powder. These powders were immediately stored at 4 °C in sterilized glass vials.

2.3. Bulk composition

The bulk composition of CMSCP and BMSCP was performed according to the AOAC (Horwitz & Latimer, 2000) and analytic methods described by Schuck et al. (2012). Indeed, the fat content was analyzed using Gerber method by dissolving approximately 2.5 g of powder in 10 ml of sulfuric acid which was then covered with Isoamyl alcohol (1 ml). The mixture was subjected to centrifugation for 5 min and then the butyrometer was immersed rapidly in a water bath heated to 70 °C for 5 min to promote separation between the dissolved lipid phase and the other components. The fat content was read directly on the butyrometer.

The total protein, the casein and the whey proteins contents were calculated based on the determination of the total nitrogen (TN), the non-casein nitrogen (NCN), and the non-protein nitrogen (NPN) following the Kjeldahl method. The non-casein nitrogen (NCN) content was determined after acidification to a pH of 4.1 using glacial acetic acid (10%, v/v). The milk samples were then adjusted to their isoelectric pH (pHi = 4.3 and 4.6 for camel sodium caseinate and cow milk sodium caseinate, respectively) using a 1M sodium acetate solution. The mixture obtained was filtered using Whatman No. 42 paper (diameter 125 mm, Whatman Int. Ltd., Maidstone, UK). The non-protein nitrogen (NPN) content was obtained by adding 40 ml of a 15% (v/v) trichloroacetic acid solution. After precipitation of all proteins, the supernatant was carefully filtered through Whatman No. 40 paper (diameter 125 mm, Whatman Int. Ltd., Maidstone, UK). Subsequently, total proteins ($=(\text{TN}-\text{NPN}) \times 6.38$), caseins ($=(\text{TN}-\text{NCN}) \times 6.38$), and whey proteins ($=(\text{NCN}-\text{NPN}) \times 6.38$) were evaluated and expressed in $\text{g } 100 \text{ g}^{-1}$.

The total solids content was determined by mixing CMSCP and BMSCP with Fontainebleau sand and drying the mixture in a ventilated oven at 102 ± 2 °C for at least 5 h. The dry matter was then measured based on the difference in weight before and after drying. The ash content was measured by incinerating the dry matter of each powder in a muffle furnace for 7 h at 550 °C. Finally, the lactose was estimated by subtracting the other component contents (fats, proteins and ash) from the total solids.

2.4. Size distribution

The size distribution of CMSCP and BMSCP particles was determined using a light laser scattering Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK) equipped with a dry powder feeder (Scirocco, 2000);

Malvern Instruments, Worcestershire, UK). The powder feeder was supplied with a dispersive air pressure of 4 bars and vibrated at a rate of 40%. The d_{50} and span were chosen as a size distribution indicator as recommended by Nikolova et al. (2014).

$$\text{span} = \frac{d_{90} - d_{10}}{d_{50}}$$

where d_{10} , d_{50} , and d_{90} indicate the powder particle size lying below 10, 50, and 90% of the whole distribution, respectively.

2.5. X-ray photoelectron spectroscopy

The surface composition of CMSCP and BMSCP were estimated using X-ray photoelectron spectroscopy (XPS) as detailed by Gaiani et al. (2011). The XPS analyses were conducted using a Kratos Axis Ultra spectrometer (Kratos Analytical, Manchester, UK) working with a monochromatic AlK α X-ray source ($E = 1486.6$ eV; $P = 90$ W), under an ultra-high vacuum (10^{-8} Pa) and activated charge neutralizer. Powder samples were dusted onto double-sided conductive adhesive tape, which was then stuck to a holder piece. The assembly was then degassed overnight prior to analysis. The analyzed area was of about 300×600 μm with a depth of 6 to 10 nm. This depth represents the effective attenuation length of the emitted electrons during photoelectron kinetic energy. The XPS spectra were derived from 160 eV analyzer pass energy with 1.0 eV step size. For high-resolution regions, the system was operating with 20 eV analyzer pass energy with a step size of 0.05 eV for C $1s$ and step size of 0.1 eV for O $1s$ and N $1s$. In all cases, the XPS system was operating in hybrid lens mode. The obtained spectra were analyzed using the Vision software from Kratos (Vision 2.2.2) based on the photoemission cross sections and the transmission coefficients provided by the Vision package.

The XPS spectra of CMSCP and BMSCP are presented Figs. 2 and 3, respectively. Using these spectra, the relative atomic concentrations of carbon, oxygen, and nitrogen in the powder surface were quantified. In order to convert the obtained atomic concentrations into lactose, protein and fats, Fäldt & Bergenstähl (1994) proposed the equation system below which allowed the quantification of the powder surface content:

$$I^C = \alpha P I^{Cp} + \alpha' L I^{CLa} + \alpha'' F I^{CLi} \quad (1)$$

$$I^O = \alpha P I^{Op} + \alpha' L I^{OLa} + \alpha'' F I^{OLi} \quad (2)$$

$$I^N = \alpha P I^{Np} + \alpha' L I^{NLa} + \alpha'' F I^{NLI} \quad (3)$$

The I^C , I^O , and I^N are calculated from the integration of the XPS peaks areas of the C $1s$, O $1s$ and N $1s$ and corresponds the mole fractions of carbon, oxygen, and nitrogen at the sample surface, respectively. The peaks integration was started by a Shirley background subtraction to remove inelastic scattering contributions. Afterward the peaks were fitted using a mixed Gaussian–Lorentzian line shape. The I^{Cp} , I^{CLa} , and I^{CLi} correspond to the mole fractions of carbon in proteins, lactose, and fat; The I^{Op} , I^{OLa} , and I^{OLi} correspond to the mole fractions of oxygen in proteins, lactose, and fat; The I^{Np} , I^{NLa} , and I^{NLI} correspond to the mole fractions of nitrogen in proteins, lactose, and fat. These mole fractions were estimated by studying the surface composition of pure fractions of casein, whey, anhydrous fat, and lactose monohydrate powders (Gaiani et al., 2010). The CMSCP and BMSCP surface proteins, lactose and fats contents is deduced by solving the matrix and calculating the αP , $\alpha' L$, and $\alpha'' F$, respectively. The surface hydrophobicity corresponds to ratio (C/O) between atomic concentration of carbone and oxygen (in%).

2.6. FTIR analysis

The absorption spectra of CMSCP and BMSCP were obtained by FT-IR spectroscopy (PerkinElmer®, Spectrum™ 100, Singapore) equipped with attenuated total reflectance (ATR) accessory containing a

diamond/ZnSe crystal (Lajnaf et al., 2020). FTIR spectra were collected in the mid infrared (MIR) region (4000 to 600 cm^{-1}) at 20 °C. The scanning rate was 20 kHz with a resolution of 4 cm^{-1} .

2.7. Turbiscan measurement

Rehydration kinetics and properties of CMSCP and BMSCP were determined by static turbidity measurements using a Turbiscan LAB™ 2000 (Formulacion, Ramonville St. Agne, France). Turbiscan LAB™ turbidity measurements make it possible to identify and monitor changes in the systems maintained in equilibrium over time based on Multiple Light Scattering (MLS). The apparatus has a detection head equipped with a near-infrared light source (860 nm). The detection head of the Turbiscan LAB™ is equipped with a pulsed light-emitting diode emitting a wavelength in the near infrared ($\lambda = 880$ nm). The light beam is projected perpendicularly to a cylindrical glass measuring cell (Height: 72 mm, diameter 21 mm). The Turbiscan LAB™ operated in 'SMART' mode (only the 100 most relevant scans are used for further calculations). During a scan, the optical scanner head scans the sample to a maximum height of 55 mm every 30 s. Incident radiation is collected every 40 μm using two types of synchronized optical detectors (180° transmission detector and 45° backscatter detector). The intensity of the incident radiation is converted into turbidity and constitutes the raw data (in %). Data related to backscattering turbidity was then collected and used to reflect the presence of opaque dispersions.

Before each series of analyses, the Turbiscan LAB™ was stabilized at 25 °C for 30 min. After stabilization, the TurbiSoft software (version 2.2.0.82, Formulacion SAS, Union, France) was programmed to perform analyses in 'SMART' mode for 4 h. The measuring cell was filled with 20 ml MiliQ water and inserted into the measuring slot. After 2 min of scanning, a quantity of 0.5 g of each milk powder was poured out through a funnel without disruption or stirring. The tested powder concentration during rehydration was equal to 0.025 g/ml. This concentration was chosen to avoid overflow of the powder at the level of the measuring cell of the Turbiscan LAB™. The data were presented after subtraction of the first scan (MiliQ water).

2.8. Statistical analysis

The whole experiment was carried out three times for statistical accuracy. All analyses and measurements in this work were conducted in triplicate. The statistical differences ($p < 0.05$) were examined using SPSS 19 software following descriptive tests including the student's t -test with a confidence level of 95 %.

3. Results and discussion

3.1. Physicochemical characterization

3.1.1. Bulk composition

The composition of camel and bovine milk sodium caseinate powder (CMSCP and BMSCP, respectively) is presented in Table 1. The produced powders presented similar total fat (10.0 ± 0.1 g 100 g^{-1} , $p > 0.05$) and ash (5.6 ± 0.1 g 100 g^{-1} , $p > 0.05$) contents. However, the results for CMSCP indicated slightly lower protein (71.9 ± 0.1 g 100 g^{-1} against 73.3 ± 0.1 g 100 g^{-1} , $p < 0.05$) and higher lactose contents (7.2 ± 0.1 g 100 g^{-1} against 5.1 ± 0.1 g 100 g^{-1} , $p > 0.05$). Compared to CMSCP, the composition of bovine sodium caseinate powder (BMSCP) has been extensively studied (Deeth & Hartanto, 2009; Gaiani et al., 2005; Gaiani et al., 2007 a). These authors reported that the sodium caseinate powder is composed of 0.9 to 1.5 g 100 g^{-1} of fat, 89 to 95 g 100 g^{-1} of protein, 0.2 g 100 g^{-1} of lactose and 3.3 to 5 g 100 g^{-1} of minerals. The composition of CMSCP and BMSCP were in line with these previous values except for total fat (10%) which is untypical. The produced powder could be then considered as a model system to evaluate the feasibility and accuracy of the applied methods to understand the

surface composition of sodium caseinate powders.

3.1.2. The size distribution

The size distribution is an important physical indicator of the powder production. In the current study, analysis of particles size distribution indicated that CMSCP had significantly lower d_{50} than that of BMSCP ($5.1 \pm 0.1 \mu\text{m}$ against $9.9 \pm 0.2 \mu\text{m}$, $p < 0.05$). Such difference could be related to the differences in the physicochemical characteristics of both sodium caseinate dispersion before drying. Besides, the span value was usually used to evaluate the width of the size distribution. For both CMSCP and BMSCP, the span values were equal to 2.5 ± 0.1 and 2.3 ± 0.1 . Analysis of Both indicators, indicated that the produced camel and bovine sodium caseinate milk powders exhibited a narrow size distribution with very low d_{50} . This indicated that these powders were composed of fine particles. In general, depending on feed properties (e.g. composition and concentration) (Abdullah et al., 2021) and the spray-dryer characteristics (Nijdam & Langrish, 2005), the size distribution of spray dried solution can vary largely. The used spray dryer in the current study was a laboratory scale dryer which produces fine particles (Nijdam & Langrish, 2005; Zouari et al., 2021).

3.2. Infrared spectroscopic analysis

The FT-IR profiles of BMSCP and CMSCP are presented in Fig. 1A and B, respectively. The FT-IR spectrum is a useful tool to provide valuable information on the protein structure and the environment of the produced powders (Ahmadi et al., 2023). Analysis of the infrared profiles of CMSCP and BMSCP indicated four common essential peaks at the region of $3500\text{--}3000 \text{ cm}^{-1}$, $2900\text{--}3000 \text{ cm}^{-1}$, $1600\text{--}1700 \text{ cm}^{-1}$, and $1500\text{--}1600 \text{ cm}^{-1}$. An additional peak was only observed for CMSCP at 1037 cm^{-1} .

Peaks in the region of $3500\text{--}3000 \text{ cm}^{-1}$ corresponded to the O-H and N-H stretch of amide A and primary amine, while, those in the region of $2800\text{--}3000 \text{ cm}^{-1}$ indicated the stretching vibration of C-H which are assigned to the vibrations of carbonyl groups of fatty acids present in dairy products (Botelho et al., 2015; Upadhyay et al., 2018). FT-IR profiles showed that broad O-H and N-H stretching peak are observed at 3312 cm^{-1} and 3286 cm^{-1} for BMSCP and CMSCP, respectively. These wavenumbers indicate a strong hydrogen bonding and the presence of

protein backbone groups characteristic of caseins. The lowest wavenumber was observed for CMSCP as compared to BMSCP, indicating stronger hydrogen bonding and extensive hydrophobic inter-protein linkage. This suggested that caseins in CMSCP are mostly aggregated and may show low rehydration properties. The C-H stretching vibrations at 2928 cm^{-1} and 2922 cm^{-1} for BMSCP and CMSCP, respectively, which are related to CH_2 and CH_3 groups further confirm the aliphatic structure among protein side chains.

Furthermore, the peaks observed at $1600\text{--}1700 \text{ cm}^{-1}$ and $1500\text{--}1600 \text{ cm}^{-1}$ corresponds to Amide I and Amide II regions, respectively. Amide I and Amide II regions are strongly related to the peptide bonds (CO-NH) (Andrade et al., 2019; Wang et al., 2018). The amide I band for both CMSCP and BMSCP was observed at 1641 cm^{-1} . This wavelength corresponds to the band of the C=O stretching vibrations and describes the β -sheet structure (Kong & Yu, 2007). Indeed, this band was associated with the secondary structure of β -casein as reported by (Cao et al., 2019). The amide II band is related to C-N and N-H stretching vibrations. Amide II peak for CMSCP was observed at a wavenumber of 1536 cm^{-1} which was slightly higher than that observed for BMSCP (wavenumber = 1510 cm^{-1}). Such a decrease could be related to the alteration of some hydrogen bonds and the enhancement of casein/casein interaction and aggregation in CMSCP.

The shared Amide I intensity at 1641 cm^{-1} suggested that both sodium caseinates maintain broadly similar secondary structure distributions. However, the different Amide II positions (1510 and 1536 cm^{-1}) indicated that the side chain interactions differ between the two species' caseins.

The supplementary peak at 1037 cm^{-1} for CMSCP indicates C-O stretching vibrations, which may arise from carbohydrate interactions with the protein matrix (Andrade et al., 2019; Arrieta et al., 2013). A similar peak was reported for a complex sodium caseinate/glycerol film (D'Incecco et al., 2025) reflecting strong binding interactions between sodium caseinate and the hydroxyl groups of glycerol. In case of CMSCP, this peak may indicate an interaction of camel milk caseins with the free glycerol group of camel milk fat since they are strongly located at the powder surface (Table 1).

Actually, it is well-known that camel and bovine milks show different caseins amount, structure and amino-acids composition (Harizi et al.,

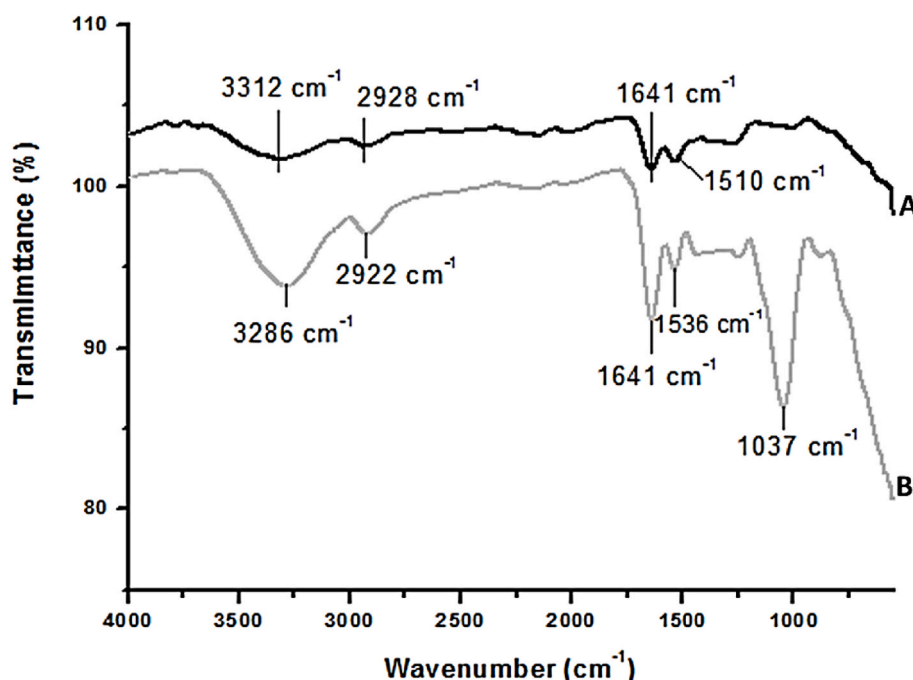


Fig. 1. FT-IR profiles of BMSCP (A) CMSCP (B).

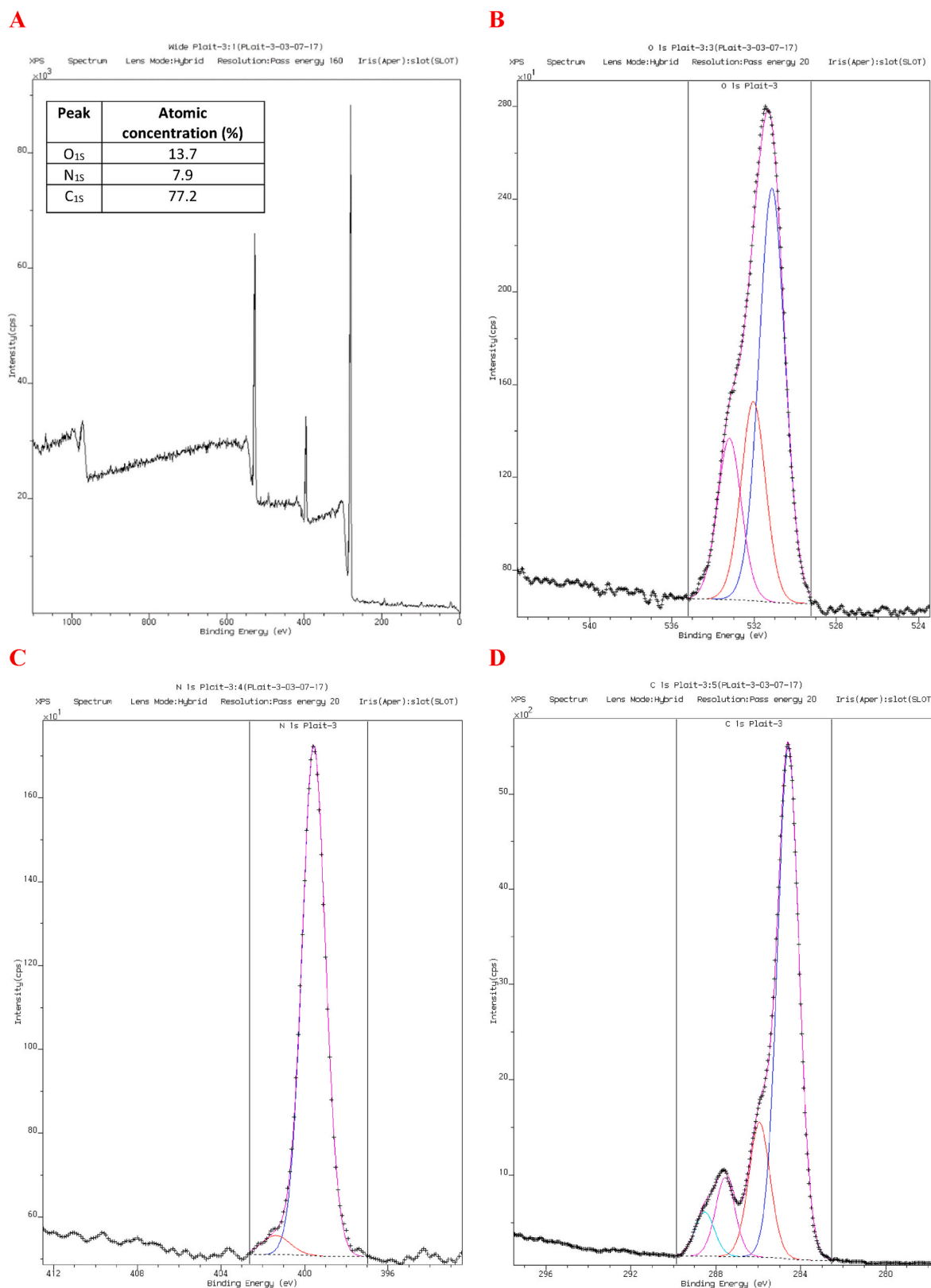


Fig. 2. Typical XPS (A) survey and high-resolution spectra of Oxygen 'O_{1s}' (B), Nitrogen 'N_{1s}' (C) and Carbone 'C_{1s}' (D) of CMSCP.

2024). It is important to highlight that camel milk presented higher β -casein and lower κ -casein which indicate that more hydrophobic interactions could be observed for camel milk casein (Zouari et al., 2018). While most of the caseins (i.e. β -casein, α -casein and κ -casein) remain stable after drying (Zouari et al., 2020b), they may aggregate and

develop some insoluble particles (Lajnaf et al., 2023). Besides, it is known that drying, due to water removal, promotes protein-protein interaction through hydrogen and hydrophobic bonds (Mujawar et al., 2014). This resulted in a downshift of the N-H/O-H bonds to a lower frequency as observed for CMSCP (3286 cm^{-1}). Also, the low water

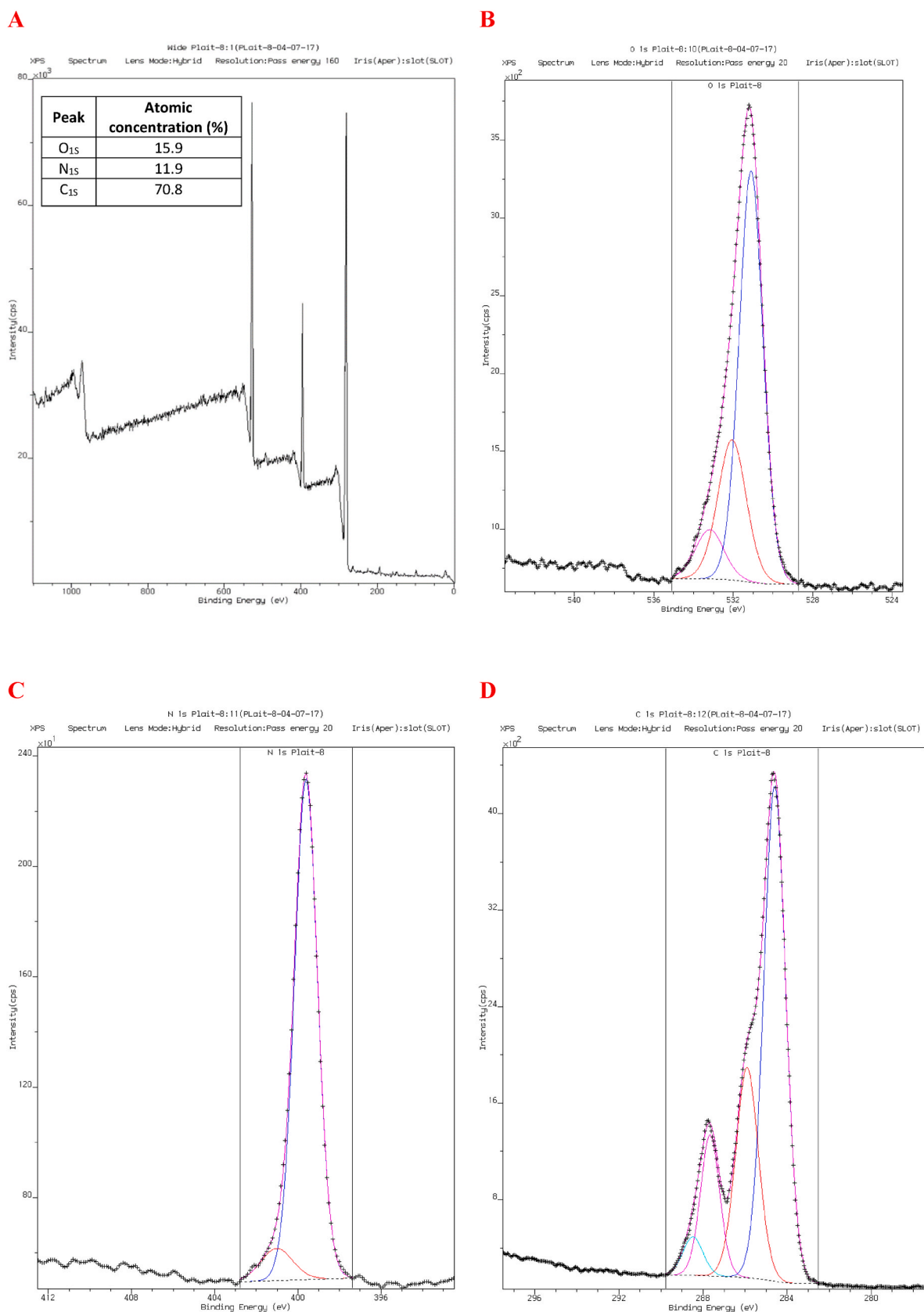


Fig. 3. Typical XPS (A) survey and high-resolution spectra of Oxygen 'O_{1s}' (B), Nitrogen 'N_{1s}' (C) and Carbone 'C_{1s}' (D) of BMSCP.

activity and/or availability in the produced powders ($a_w = 0.24$, Table 1), restricted the proteins mobility which favors the development of β sheet aggregates (Schmitt et al., 2009). Since CMSCP had more β -casein content and showed higher intensity Amid II intensity than that observed for BMSCP, it could be suggested that CMSCP has more β sheet aggregates which may limit its interaction with water.

For CMSCP and giving the decreased O-H and N-H stretching peak (3286 cm^{-1}), the increased Amid II band (1536 cm^{-1}) and pronounced C-O peak (1037 cm^{-1}), it is clearly that its caseins were aggregated (strong hydrophobic protein-protein interaction) with less hydrated proteins matrix (altered hydrogen bonds and/or association with camel milk fats) which could lower their rehydration capacities.

3.3. Surface chemical composition

The surface composition of spray dried dairy powders is a critical parameter for their techno-functional properties especially the rehydration. Indeed, even if CMSCP and BMSCP showed relatively similar bulk composition, their surface composition could largely be different. As a matter of fact, Kim et al., 2002 indicated that the surface of skimmed milk powder with low milk fat content (0.1 %) could be covered by up to 20% of fat. The surface composition of CMSCP and BMSCP powders is summarized in Table 1. Although both camel and bovine sodium caseinate powder presented the same fat content (10%, Table 1), the surface fat coverage of CMSCP ($48.9 \pm 2.4\%$) was significantly higher than that of BMSCP ($21.3 \pm 1.1\%$, $p < 0.05$, Table 1). Furthermore, the results indicated higher protein content of $77.8 \pm 3.9\%$ for BMSCP as compared to that of CMSCP ($50.4 \pm 2.5\%$, $p < 0.05$). It is worth noting that the surface of CMSCP presented relatively similar protein and fat distribution, while, BMSCP surface contained a protein content 3.6 times higher than that of fat.

The surface composition is derived from the relative elemental composition of CMSCP and BMSCP presented in Table 2. Analysis of the XPS survey indicated the existence of three essential peaks corresponding to carbone 'C_{1s}', nitrogen 'N_{1s}', and oxygen 'O_{1s}'. The findings indicated significantly lower nitrogen ($7.93 \pm 0.4\%$ against $11.99 \pm 0.6\%$, $p < 0.05$) and oxygen ($13.7 \pm 0.7\%$ against $15.98 \pm 0.8\%$, $p < 0.05$) contents as compared to BMSCP. It is worth noticing that a higher carbon content for CMSCP ($77.25 \pm 1\%$ against $70.86 \pm 1\%$, $p < 0.05$) was observed. This suggested that CMSCP exhibited more non-polar chemical groups at its surface compared to that of BMSCP. In the present study, the elemental composition of camel milk sodium caseinate powder was reported for the first time. However, several studies have been devoted to study the surface elemental composition of bovine milk sodium caseinate or native casein micelles powders (Gaiani et al., 2007 b; Gaiani et al., 2007 b; Jones et al., 2013; Kim et al., 2002). Based on these previous studies, the average elemental surface composition of bovine milk sodium caseinate powder was equal to 65% carbone, 18% oxygen, and 14% nitrogen.

Table 1
Bulk and surface composition of CMSCP and BMSCP.

	Powder Bulk composition (g 100g ⁻¹)		Powder surface composition (%)	
	CMSCP	BMSCP	CMSCP	BMSCP
a_w	0.248	0.241	-	-
Total solids	95.1 ± 0.4^a	94.2 ± 0.1^b	-	-
Proteins	71.9 ± 0.1^a	73.3 ± 0.1^b	50.4 ± 2.5^a	77.8 ± 3.9^b
Caseins	71.2 ± 0.1^a	73.1 ± 0.1^b	-	-
Whey	0.2 ± 0.01^a	0.2 ± 0.01^a	-	-
Total fats	10.0 ± 0.1^a	10.0 ± 0.1^a	48.9 ± 2.4^a	21.3 ± 1.1^b
Lactose	7.2 ± 0.1^a	5.1 ± 0.1^b	0 ± 0.00^a	0.2 ± 0.01^a
Ash	5.6 ± 0.1^a	5.6 ± 0.1^a	0.6 ± 0.03^a	0.6 ± 0.03^a

CMSCP: Camel milk sodium caseinate powder and BMSCP: Bovine milk sodium caseinate powder. Same letter in the same row for milks or powders represent the statistical data significance ($p \geq 0.05$).

The deconvolution of the carbon (C_{1s}) spectra indicated the presence of four distinct sub-peaks (C-(C, H), C-O, C=O and O-C=O). Importantly, higher C-(C, H) and O-C=O linkages were measured at the surface of CMSCP, meanwhile, the C-O and C=O linkages were lower (Table 2). These sub-peaks describe the different chemical functions of proteins, fats and lactose composing BMSCP and CMSCP. The results of the current study, clearly indicate that the non-polar aliphatic chain C-(C, H) predominated the surface of both CMSCP and BMSCP powders with 67.6 ± 1.0 and 56.7 ± 1.0 , respectively. It is important to notice that the polar aliphatic chain C-O and C=O were significantly higher at the surface of BMSCP compared to that of CMSCP (Table 2). The higher C-(C, H) together with the lower C-O and C=O fractions in CMSCP clearly confirmed the predominance of non-polar aliphatic carbon at its surface which induces an increase of its hydrophobicity.

The powder hydrophobicity could be estimated using the C/O ratio (Murrieta-pazos et al., 2012b). Indeed, the atomic concentration of carbon and oxygen are converted into C/O ratio. This ratio describes the surface hydrophobicity of dairy powders including sodium caseinate powders. The calculated values for C/O were equal 5.64 ± 0.3 and 4.43 ± 0.2 for CMSCP and BMSCP, respectively (Table 2). This result clearly indicated that the surface of CMSCP presented significantly higher hydrophobicity than that of BMSCP ($p \geq 0.05$, Table 2). Studies of the surface composition of dairy and milk fraction powders indicated that pure lactose and milk fat had C/O ratios of 1.2 and over 7, respectively (Nikolova et al., 2015). This indicated that an increased C/O ratio is related to the overrepresentation of non-polar aliphatic carbon chains of milkfats and/or proteins at the surface (Gaiani et al., 2006). Such carbon linkages highly indicate that the surface of CMSCP is much more hydrophobic than that of BMSCP and cannot easily link the hydrogen of water. This will deeply impact the rehydration properties of CMSCP, especially the wettability and dispersibility.

3.4. Turbidity assessment

The generated backscattering turbidity profiles are presented in Fig. 4. These profiles were used to follow the rehydration behavior of camel and bovine milk sodium caseinate powders over the time based on the turbidity changes. In order to have a better understanding of these profiles, a color gradient ranging from blue (start) to red (end) is used to illustrate the time evolution. The x-axis indicates the height in the measurement cell (top = 42 mm, bottom = 0 mm), and the y-axis shows the variation in backscattering turbidity over time. The measurement vessel could be divided to three distinct regions: the bottom region (5 to 15 mm), the central region (15 to 35 mm) and the top region (35 to 42 mm). Positive or negative shifts in backscattering turbidity at each region are related to changes in particle concentration and/or size. Such turbidity changes reflect the wettability at the top region, the dispersibility and the dissolution at the central region, and the sedimentation at the bottom. The wettability corresponds to the particles penetration into water and is followed by turbidity changes over the time (black arrow, Fig. 4). If the red color is dominant, this means that at the end of the experiment, the turbidity is still important at the top of the measurement vessel indicating that the powder is not a wettable powder. The sedimentation is the accumulation of particles at the bottom of the measurement vessel without dissolution which is followed by an important increase of the turbidity signal (double arrow, Fig. 4A). However, particle dispersion and dissolution were observed when particles dissolved in water rather than settling at the bottom. This results in a regular/uniform change in turbidity signals.

Analysis of the CMSCP rehydration profile (Fig. 4A) revealed three distinct stages. During the initial stage of rehydration (0 to 15 min, blue curves), there was a rapid decrease in the backscattering signal near the bottom (5 to 15 mm), reflecting the accumulation and sedimentation of CMSCP particles. In the top region of the measurement cell (35–42 mm), there was a significant increase in backscattering, suggesting very slow dissolution of floating, non-sedimented particles. The backscattering

Table 2
Complete elemental composition of CMSCP and BMSCP.

Elements	CMSCP	BMSCP
O _{1s} (%)	13.7 ± 0.7 ^a	15.9 ± 0.8 ^b
N _{1s} (%)	7.9 ± 0.4 ^a	11.9 ± 0.6 ^b
C _{1s} (%)	77.2 ± 1.0 ^a	70.8 ± 1.0 ^b
C-(C,H)	67.6 ± 1.0 ^a	56.7 ± 1.0 ^b
C-O	17.6 ± 0.9 ^a	25 ± 1.2 ^b
C=O	9.4 ± 0.5 ^a	14.1 ± 0.7 ^b
O-C=O	5.2 ± 0.3 ^a	4.1 ± 0.2 ^b
Stoichiometry: C\O (surface hydrophobicity)	5.6 ± 0.3 ^a	4.4 ± 0.2 ^b

CMSCP: Camel milk sodium caseinate powder and BMSCP: Bovine milk sodium caseinate powder. Same letter in the same row represent the statistical data significance ($p \geq 0.05$).

signal in the central region (15 to 35 mm) remained stable and depended clearly on the dissolution of the floating particles at the top of the measurement cell. This analysis clearly indicates that, during the first 15 min of rehydration, the CMSCP powder exhibited poor wettability (the particles remained at the top of the measurement cell) and dispersibility (dense and large particles sedimented). In the second stage of rehydration (15 to approximately 60 min, during which the curves

change from blue to green and yellow) and in the late stage (>60 min, during which the curves change from orange to red), an upward drift in backscattering was observed in the first 15 to 35 mm of the measurement cell, indicating solubilization of the CMSCP powder over time. It is important to note that the backscattering at the top or bottom of the measurement cell remains as described for the early stage. This suggests that the solubilization rate is very slow, indicating the presence of highly hydrophobic proteins and/or a high fat content on the surface. This hypothesis was confirmed by XPS analysis (Table 1), which clearly showed that the CMSCP surface is composed of hydrophobic caseins (50.4%) and fats (48.9%). This surface layer composition makes solubilizing CMSCP very difficult.

Additionally, the turbidity profiles for the BMSCP powder (Fig. 4B) revealed two stages of rehydration. The initial stage (up to 45 min, blue curve) showed smooth backscattering fluctuations alongside the measurement cell over the rehydration period. This indicates the powder wetted quickly at the top (35 to 42 mm) and dispersed homogeneously in the central region (15 to 35 mm). This behavior is the result of better instant rehydration properties, which reduce particle sedimentation at the bottom (5–15 mm). During the mid-to-late stage of rehydration (>45 min, curves ranging from green to red), the backscattering

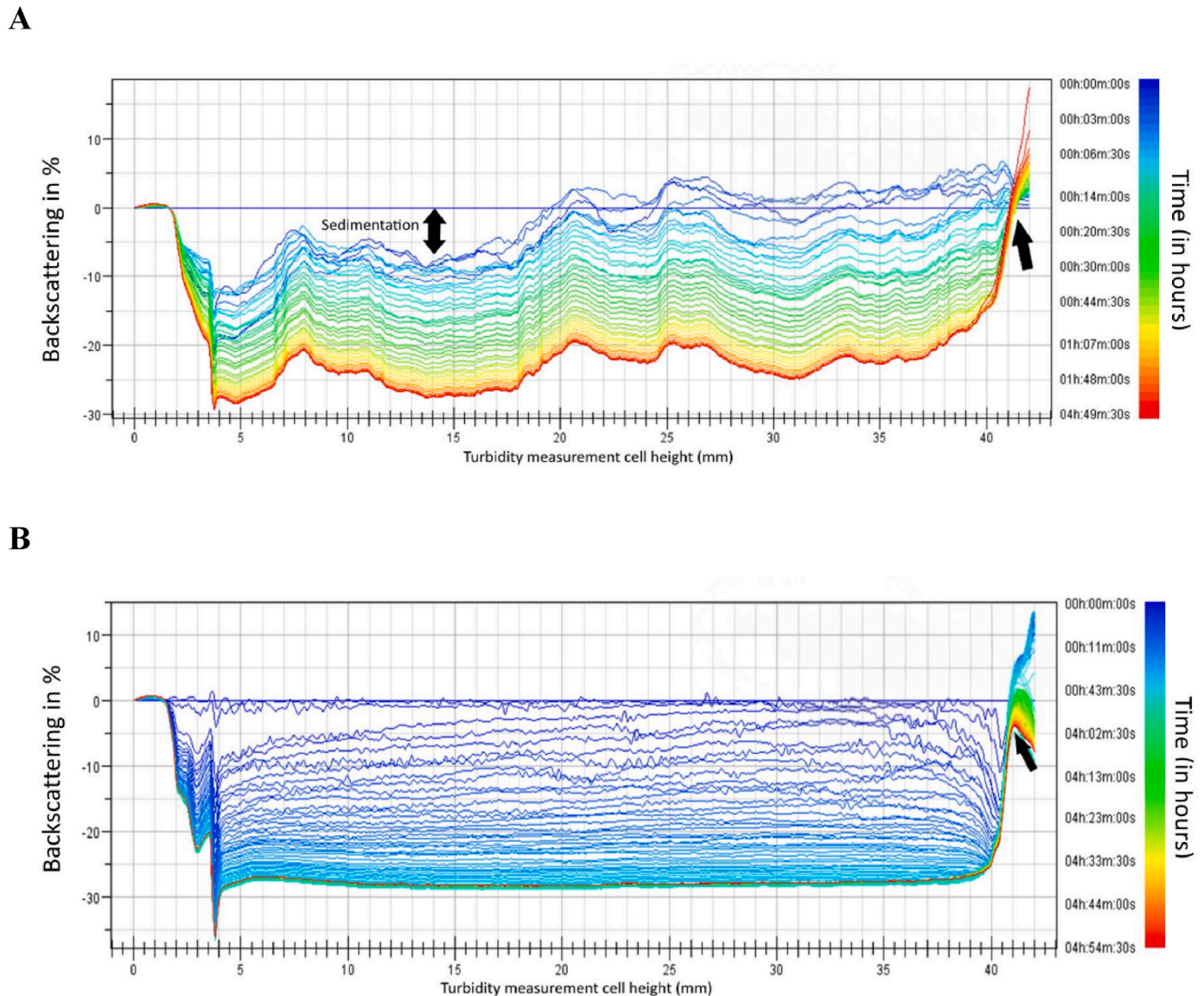


Fig. 4. Rehydration turbidity backscattering profiles of CMSCP (A) BMSCP (B).

variation remained stable and uniform over time, with no clear sedimentation occurring. This rehydration behavior indicates that BMSCP powder is highly soluble in water, demonstrating excellent wettability and dispersibility.

The observed stability and the rapid equilibration of turbidity backscattering suggest that BMSCP has superior solubilization kinetics compared to that of CMSCP. Indeed, the comparative Turbiscan analysis clearly demonstrates that BMSCP exhibits excellent dispersibility and solubility characteristics, whereas CMSCP shows slower hydration dynamics (especially the wettability) and reduced colloidal stability (sedimentation). These differences in reconstitution performance can be attributed to the surface composition of the powders and their size distribution. Indeed, the rehydration process is a complex process which is influenced by several factors including, temperature, stirring parameters, size distribution and the hydrophobicity of the dairy powders (Jiang et al., 2025). The particle size distribution is actually one of the key factors of rehydration process. It is well known that spray dried dairy powders are mainly composed of fine and large particles which influences their bulk density, surface area and porosity (Gaiani et al., 2007 b). Despite their high surface exchange area with water, fine particles (<100–150 μm) within dairy powders increase the cohesiveness thereby limiting the wettability and dispersibility (Ji et al., 2016). In the current study, the d_{50} of both produced powders is lower than 10 μm and may influence their rehydration in water.

Moreover, in the current study, BMSCP and CMSCP were not stirred during rehydration. It is acknowledged that the incorporation mode in water and stirring parameters (i.e. temperature, speed, duration, etc.) impacted the rehydration behavior of the dairy powders (Gaiani et al., 2007 b; Jeantet et al., 2010). Several researchers have indicated that stirring affects the late stage of rehydration by breaking the powder particles clusters/agglomerates and by enhancing the mass transfer to disperse and dissolve the fine particles (Angelopoulou et al., 2021; Chandrapala et al., 2014). The main objective of the current study was to link the surface characteristics of camel and bovine milk caseinate powders to their rehydration ability. Since BMSCP and CMSCP showed similar size distribution (section 3.1.2) and were not stirred, it could be concluded that their surface composition and hydrophobicity are the main factors that govern their rehydration process in water.

4. Conclusions

In the current study, camel and bovine milk sodium caseinate powders were produced using a spray drying process. Clear differences in composition, structure and function were revealed. Indeed, while both powders had similar levels of bulk fat and ash, camel milk sodium caseinate powder (CMSCP) exhibited lower protein levels and higher lactose content than those of bovine milk sodium caseinate powder (BMSCP). Surface chemical analysis indicated that CMSCP had greater carbon enrichment and a higher C/O ratio, resulting in increased surface fat coverage and enhanced hydrophobicity. Further confirmation of stronger hydrogen bonding and greater β -sheet secondary structure in CMSCP was provided by FT-IR results, consistent with its distinct protein composition and its ability to form insoluble aggregates. Turbiscan analyses showed that this hydrophobic surface hindered wetting and solubilization, resulting in slower rehydration kinetics for CMSCP as compared to that of BMSCP. Taken together, these findings suggest that the physicochemical behavior of CMSCP is largely governed by its surface fat-protein arrangement and hydrophobicity.

CRedit authorship contribution statement

Ahmed Zouari: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hamadi Attia:** Visualization, Validation, Supervision, Conceptualization. **Mohamed Ali Ayadi:** Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All the used data are presented in the manuscript

References

- Abdullah, Z., Taip, F. S., Mustapa Kamal, S. M., & Abdul Rahman, R. Z. (2021). The effect of drying temperature and sodium caseinate concentration on the functional and physical properties of spray-dried coconut milk. *Journal of Food Science and Technology*, 58(8), 3174–3182. <https://doi.org/10.1007/s13197-020-04820-9>
- Abu-Lehia, I. H. (1998). Recombined camel's milk powder. *Colloques-CIRAD*. In P. Bonnet (Ed.), *Actes du colloque, Dromadaires et chameaux, animaux laitiers/ Dromedaries and camels, milking animals* (pp. 181–184). Nouakchott, Mauritania. CIRAD Publ (1998), Ahmadi, E., Vasiljevic, T., & Huppertz, T. (2023). Influence of pH on heat-induced changes in skim milk containing various levels of micellar calcium phosphate. *Molecules*, 28(19), 6847.
- Al Haj, O. A., & Al Kanhal, H. A. (2010). Compositional, technological and nutritional aspects of dromedary camel milk. *International Dairy Journal*, 20(12), 811–821. <https://doi.org/10.1016/j.idairyj.2010.04.003>
- Andrade, J., Guimarães, C., Carlos, J., Junior, D. A., Carvalho, C., Viana, R., Natália, L., Neves, D. O., Henrique, P., José, M., Bell, V., & Carvalho, V. De (2019). FTIR-ATR determination of protein content to evaluate whey protein concentrate adulteration. *LWT - Food Science and Technology*, 99(October 2018), 166–172. <https://doi.org/10.1016/j.lwt.2018.09.079>
- Angelopoulou, D., Meunier, V., Forn, L., Niederreiter, G., Palzer, S., & Salman, A. D. (2021). Influence of localized thermal effects on the reconstitution kinetics of lactose-coated whole milk powder. *Food Research International*, 150, Article 110774.
- Arrieta, M. P., Peltzer, M. A., del Carmen Garrigós, M., & Jiménez, A. (2013). Structure and mechanical properties of sodium and calcium caseinate edible active films with carvacrol. *Journal of Food Engineering*, 114(4), 486–494.
- Botelho, B. G., Reis, N., Oliveira, L. S., & Sena, M. M. (2015). Development and analytical validation of a screening method for simultaneous detection of five adulterants in raw milk using mid-infrared spectroscopy and PLS-DA. *Food Chemistry*, 181, 31–37.
- Cao, X., He, Y., Kong, Y., Mei, X., Huo, Y., He, Y., & Liu, J. (2019). Elucidating the interaction mechanism of eriocitrin with β -casein by multi-spectroscopic and molecular simulation methods. *Food Hydrocolloids*, 94, 63–70.
- Chandrapala, J., Martin, G. J. O., Kentish, S. E., & Ashokkumar, M. (2014). Dissolution and reconstitution of casein micelle containing dairy powders by high shear using ultrasonic and physical methods. *Ultrasonics Sonochemistry*, 21(5), 1658–1665.
- Deeth, H. C., & Hartanto, J. (2009). Chemistry of milk—Role of constituents in evaporation and drying. In A. Tamim (Ed.), *Dairy powders and concentrated products*. Chichester, UK: Blackwell Publishing.
- Desouky, M. M., Shalaby, S. M., & Soryal, K. A. (2013). Compositional, rheological and organoleptic qualities of camel milk labneh as affected by some milk heat treatments, 8(2), 118–130 <https://doi.org/10.5829/idosi.wjdfs.2013.8.2.1124>.
- D'Incecco, P., Gerna, S., Sindaco, M., Pellegrino, L., Barbiroli, A., Rosi, V., & Limbo, S. (2025). Functionalization of sodium caseinate for production of neat films: Effects of casein crosslinking induced by heating at alkaline pH or light exposure. *Foods*, 14 (16), 2764.
- Fäldt, P., & Bergenstahl, B. (1994). The surface composition of spray-dried protein-lactose powders. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 90 (2–3), 183–190. [https://doi.org/10.1016/0927-7757\(94\)02914-8](https://doi.org/10.1016/0927-7757(94)02914-8)
- Felix da Silva, D., Ahrné, L., Ipsen, R., & Houghard, A. B. (2018). Casein-based powders: Characteristics and rehydration properties. *Comprehensive Reviews in Food Science and Food Safety*, 17(1), 240–254. <https://doi.org/10.1111/1541-4337.12319>
- Gaiani, C., Banon, S., Scher, J., Schuck, P., & Hardy, J. (2005). Use of a turbidity sensor to characterize micellar casein powder rehydration: Influence of some technological effects. *Journal of Dairy Science*, 88(8), 2700–2706. [https://doi.org/10.3168/jds.S0022-0302\(05\)72948-9](https://doi.org/10.3168/jds.S0022-0302(05)72948-9)
- Gaiani, C., Ehrhardt, J. J., Scher, J., Hardy, J., Desobry, S., & Banon, S. (2006). Surface composition of dairy powders observed by X-ray photoelectron spectroscopy and

- effects on their rehydration properties. *Colloids and Surfaces B: Biointerfaces*, 49(1), 71–78.
- Gaiani, C., Morand, M., Sanchez, C., Tehrani, E. A., Jacquot, M., Schuck, P., Jeantet, R., & Scher, J. (2010). How surface composition of high milk proteins powders is influenced by spray-drying temperature. *Colloids and Surfaces B: Biointerfaces*, 75, 377–384. <https://doi.org/10.1016/j.colsurfb.2009.09.016>
- Gaiani, C., Mullet, M., Arab-Tehrany, E., Jacquot, M., Perroud, C., Renard, a., & Scher, J. (2011). Milk proteins differentiation and competitive adsorption during spray-drying. *Food Hydrocolloids*, 25(5), 983–990. <https://doi.org/10.1016/j.foodhyd.2010.09.013>
- Gaiani, Scher, J., Ehrhardt, J. J., Linder, M., Schuck, P., Desobry, S., & Banon, S. (2007a). Relationships between dairy powder surface composition and wetting properties during storage: Importance of residual lipids. *Journal of Agricultural and Food Chemistry*, 55(16), 6561–6567. <https://doi.org/10.1021/jf070364b>
- Gaiani, C., Scher, J., Schuck, P., Desobry, S., & Banon, S. (2009). Use of a turbidity sensor to determine dairy powder rehydration properties. *Powder Technology*, 190(1–2), 2–5.
- Gaiani, Schuck, P., Scher, J., Desobry, S., & Banon, S. (2007b). Dairy powder rehydration: influence of protein state, incorporation mode, and agglomeration. *Journal of Dairy Science*, 90(2), 570–581. [https://doi.org/10.3168/jds.S0022-0302\(07\)71540-0](https://doi.org/10.3168/jds.S0022-0302(07)71540-0)
- Harizi, N., Zouari, A., Rokbeni, N., Ben Zid, M., M'hiri, N., Salem, A., Ayadi, M. A., & Boudhrioua, N. (2024). Amino acids and protein profiles of defatted camel and cow milk fractions: correlation with their in vitro antioxidant and antidiabetic activities. *Frontiers in Nutrition*, 10, Article 1295878.
- Horwitz, W., & Latimer, G. (2000). *Official methods of analysis of AOAC international*. Gaithersburg MA, USA: Association of Official Analytical Chemist.
- Hussain, R., Gaiani, C., Aberkane, L., & Scher, J. (2011). Characterization of high-milk-protein powders upon rehydration under various salt concentrations. *Journal of Dairy Science*, 94(1), 14–23. <https://doi.org/10.3168/jds.2010-3323>
- Hussain, R., Gaiani, C., & Scher, J. (2012). From high milk protein powders to the rehydrated dispersions in variable ionic environments: A review. *Journal of Food Engineering*, 113(3), 486–503. <https://doi.org/10.1016/j.jfoodeng.2012.06.011>
- Jeantet, R., Schuck, P., Six, T., Andre, C., & Delaplace, G. (2010). The influence of stirring speed, temperature and solid concentration on the rehydration time of micellar casein powder. *Dairy Science & Technology*, 90(2), 225–236.
- Ji, J., Fitzpatrick, J., Cronin, K., Maguire, P., Zhang, H., & Miao, S. (2016). Rehydration behaviours of high protein dairy powders: The influence of agglomeration on wettability, dispersibility and solubility. *Food Hydrocolloids*, 58, 194–203.
- Jiang, H., Zhang, N., Xie, L., Li, G., Chen, L., & Liao, Z. (2025). A comprehensive review of the rehydration of instant powders: Mechanisms, influencing factors, and improvement strategies. *Foods*, 14(16), 2883.
- Jones, J. R., Prime, D., Leaper, M. C., Richardson, D. J., Rielly, C. D., & Stapley, A. G. F. (2013). Effect of processing variables and bulk composition on the surface composition of spray dried powders of a model food system, 118(1), 19–30 <https://doi.org/10.1016/j.jfoodeng.2013.03.027>
- Kim, E. H.-J., Chen, X. D., & Pearce, D. (2002). Surface characterization of four industrial spray-dried dairy powders in relation to chemical composition, structure and wetting property. *Colloids and Surfaces B: Biointerfaces*, 26(3), 197–212. [https://doi.org/10.1016/S0927-7765\(01\)00334-4](https://doi.org/10.1016/S0927-7765(01)00334-4)
- Kim, E. H.-J., Chen, X. D., & Pearce, D. (2009). Surface composition of industrial spray-dried milk powders. 3. Changes in the surface composition during long-term storage. *Journal of Food Engineering*, 94(2), 182–191. <https://doi.org/10.1016/j.jfoodeng.2008.12.001>
- Kong, J., & Yu, S. (2007). Fourier transform infrared spectroscopic analysis of protein secondary structures. *Acta Biochimica et Biophysica Sinica*, 39(8), 549–559.
- Konuspaveva, G., Faye, B., & Loiseau, G. (2009). The composition of camel milk: A meta-analysis of the literature data. *Journal of Food Composition and Analysis*, 22, 95–101. <https://doi.org/10.1016/j.jfca.2008.09.008>
- Lajnaf, R., Attia, H., & Ayadi, M. A. (2023). Chemistry of camel milk proteins in food processing. In *Food processing and preservation*. IntechOpen.
- Lajnaf, R., Zouari, A., Trigui, I., Attia, H., & Ayadi, M. A. (2020). Effect of different heating temperatures on foaming properties of camel milk proteins: A comparison with bovine milk proteins. *International Dairy Journal*, 104. <https://doi.org/10.1016/j.idairyj.2020.104643>
- Loi, C. C., Eyres, G. T., Silcock, P., & Birch, E. J. (2020). Preparation and characterisation of a novel emulsifier system based on glycerol monooleate by spray-drying. *Journal of Food Engineering*, 285(April), Article 110100. <https://doi.org/10.1016/j.jfoodeng.2020.110100>
- Marafon, A. P., Sumi, A., Alcântara, M. R., Tamime, A. Y., & De Oliveira, M. N. (2011). Optimization of the rheological properties of probiotic yoghurts supplemented with milk proteins. *LWT - Food Science and Technology*, 44(2), 511–519. <https://doi.org/10.1016/j.lwt.2010.09.005>
- Martínez-Padilla, L. P., García-Mena, V., Casas-Alencáster, N. B., & Sosa-Herrera, M. G. (2014). Foaming properties of skim milk powder fortified with milk proteins. *International Dairy Journal*, 36(1), 21–28. <https://doi.org/10.1016/j.idairyj.2013.11.011>
- McSweeney, D. J., Maidannyk, V., Montgomery, S., O'Mahony, J. A., & McCarthy, N. A. (2020). The influence of composition and manufacturing approach on the physical and rehydration properties of milk protein concentrate powders. *Foods*, 9(2). <https://doi.org/10.3390/foods9020236>
- Mujawar, L. H., Kuerten, J. G. M., Siregar, D. P., van Amerongen, A., & Norde, W. (2014). Influence of the relative humidity on the morphology of inkjet printed spots of IgG on a non-porous substrate. *RSC Adv*, 4(2014), 19380–19388.
- Murrieta-Pazos, I., Gaiani, C., Galet, L., Calvet, R., Cuq, B., & Scher, J. (2012a). Food powders: Surface and form characterization revisited. *Journal of Food Engineering*, 112(1–2), 1–21. <https://doi.org/10.1016/j.jfoodeng.2012.03.002>
- Murrieta-pazos, I., Gaiani, C., Galet, L., & Scher, J. (2012b). Food hydrocolloids composition gradient from surface to core in dairy powders: Agglomeration effect. *Food Hydrocolloids*, 26(1), 149–158. <https://doi.org/10.1016/j.foodhyd.2011.05.003>
- Nijdam, J. J., & Langrish, T. A. G. (2005). An investigation of milk powders produced by a laboratory-scale spray dryer. *Drying Technology*, 23(5), 1043–1056. <https://doi.org/10.1081/DRT-200060208>
- Nijdam, J. J., & Langrish, T. A. G. (2006). The effect of surface composition on the functional properties of milk powders. *Journal of Food Engineering*, 77(4), 919–925. <https://doi.org/10.1016/j.jfoodeng.2005.08.020>
- Nikolova, Y., Petit, J., Sanders, C., Gianfrancesco, a., Desbenoit, N., Frache, G., Francius, G., Scher, J., & Gaiani, C. (2014). Is it possible to modulate the structure of skim milk particle through drying process and parameters? *Journal of Food Engineering*, 142, 179–189. <https://doi.org/10.1016/j.jfoodeng.2014.05.026>
- Nikolova, Y., Petit, J., Sanders, C., Gianfrancesco, A., Scher, J., & Gaiani, C. (2015). Toward a better determination of dairy powders surface composition through XPS matrices development. *Colloids and Surfaces B: Biointerfaces*, 125, 12–20.
- Orlien, V., Boserup, L., & Olsen, K. (2010). Casein micelle dissociation in skim milk during high-pressure treatment: Effects of pressure, pH, and temperature. *Journal of Dairy Science*, 93(1), 12–18.
- Qi, X., van der Berg, F. W. J., Malmos, K. G., Kirkensgaard, J. J. K., & Bakalis, S. (2026). Kinetics of lactose crystallization in milk powders – Preconditioning to preserve functionality during storage. *International Dairy Journal*, 174, Article 106503. <https://doi.org/10.1016/j.idairyj.2025.106503>
- Roy, S., & Amamcharla, J. K. (2025). Invited review: Recent developments in understanding the rehydration characteristics of high-protein dairy powders. *Journal of Dairy Science*, 108(3), 2133–2151.
- Sadat, A., Ezzatpanah, H., & Bakhoda, H. (2017). Solubility and structure of milk powders manufactured with the addition of disodium phosphate and tetrasodium pyrophosphate mixtures. *International Journal of Food Properties*, 20(11), 2645–2657. <https://doi.org/10.1080/10942912.2016.1247272>
- Schmitt, C., Bovay, C., Vuillomenet, A.-M., Rouvet, M., Bovetto, L., Barbar, R., & Sanchez, C. (2009). Multiscale characterization of individualized β -lactoglobulin microgels formed upon heat treatment under narrow pH range conditions. *Langmuir*, 25(14), 7899–7909.
- Schuck, P., Jeantet, R., & Dolivet, A. (2012). *Analytical methods for food and dairy powders*. John Wiley & Sons.
- Shrestha, A. K., Howes, T., Adhikari, B. P., Wood, B. J., & Bhandari, B. R. (2007). Effect of protein concentration on the surface composition, water sorption and glass transition temperature of spray-dried skim milk powders. *Food Chemistry*, 104(4), 1436–1444. <https://doi.org/10.1016/j.foodchem.2007.02.015>
- Upadhyay, N., Jaiswal, P., & Jha, S. N. (2018). Application of attenuated total reflectance fourier transform infrared spectroscopy (ATR-FTIR) in MIR range coupled with chemometrics for detection of pig body fat in pure ghee (heat clarified milk fat). *Journal of Molecular Structure*, 1153, 275–281.
- Vignolles, Lopez, C., Ehrhardt, J.-J., Lambert, J., Méjean, S., Jeantet, R., & Schuck, P. (2009). Methods' combination to investigate the suprastructure, composition and properties of fat in fat-filled dairy powders. *Journal of Food Engineering*, 94(2), 154–162.
- Wang, X., Esquerre, C., Downey, G., Henihan, L., O'Callaghan, D., & O'Donnell, C. (2018). Feasibility of discriminating dried dairy ingredients and preheat treatments using mid-infrared and Raman spectroscopy. *Food Analytical Methods*, 11(5), 1380–1389.
- Zouari, A., Lajnaf, R., Lopez, C., Schuck, P., Attia, H., & Ayadi, M. A. (2021). Physicochemical, techno-functional, and fat melting properties of spray-dried camel and bovine milk powders. *Journal of Food Science*, 86(1), 103–111. <https://doi.org/10.1111/1750-3841.15550>
- Zouari, A., Marchesseau, S., Chevalier-Lucia, D., Raffard, G., Ayadi, M. A., & Picart-Palmade, L. (2018). Acid gelation of raw and reconstituted spray-dried dromedary milk: A dynamic approach of gel structuring. *International Dairy Journal*, 81, 95–103. <https://doi.org/10.1016/j.idairyj.2018.01.009>
- Zouari, A., Schuck, P., Gaucheron, F., Triki, M., Delaplace, G., Gauzelin-Gaiani, C., Lopez, C., Attia, H., & Ayadi, M.A. (2020a). Microstructure and chemical composition of camel and cow milk powders' surface. *LWT*, 117, Article 108693. <https://doi.org/10.1016/j.lwt.2019.108693>
- Zouari, A., Briard-Bion, V., Schuck, P., Gaucheron, F., Delaplace, G., Attia, H., & Ayadi, M.A. (2020b). Changes in physical and biochemical properties of spray dried camel and bovine milk powders. *LWT*, 128, Article 109437. <https://doi.org/10.1016/j.lwt.2020.109437>