Chapter

Dairy Powders Processing and Characterization

Ahmed Zouari, Mondher Mzoughi and Mohamed Ali Ayadi

Abstract

Milk and dairy products are naturally exposed to multiple microbiological, physical and biochemical degradations. Such products require one or more stabilization operations during processing and storing to ensure acceptable sanitary and sensory qualities to the consumer. Several stabilization treatments, such as drying, are commonly applied to dairy products. A successful drying operation requires an in-depth understanding of the physic-chemical changes that occur during the production and storage of dairy powders. Mastering these changes is mandatory to avoid dairy powder degradations, which mainly depend on water dynamics and thermodynamic characteristics of the produced powder. This chapter gives an overview of dairy powder production through the understanding of the powder production principals. A discussion of some essential powder characteristics will be provided. Finally, an overview of the production of camel milk powder will be provided and will be compared with that of cow milk powder.

Keywords: milk, drying, pretreatments, water sorption, glass transition, microstructure

1. Introduction

Milk and dairy products have always been considered as a primary source of nutrients in the human diet. These products are mainly composed of water (up to 90%), proteins, lipids, lactose and minerals. Some of them are subjected to a drying process and are used as food ingredients in various formulations.

Actually, the drying technologies were mainly developed to facilitate the storage and transportation of dairy products as well as to reduce their cost. The ultimate goal of drying is to increase the shelf life of dairy products for a long period of time (up to 2 years) without significant loss of quality [1]. In fact, the transformation of milk into powder allows the elimination of a large amount of water and therefore reduces the milk volume and degradation risks. However, the transition from a liquid state to powder can induce some physicochemical changes in dairy matrix. Indeed, although converting milk and dairy products into powders seems to be advantageous, some technical and physicochemical limitations could be consequent. In fact, it was reported that the biochemical composition of the dairy matrix could limit heat and mass (mainly water) transfers during drying [2, 3]. The presence of sufficient water often makes dairy powders susceptible to multiple microbiological, biochemical and physical deteriorations [4, 5]. It was reported that some of these deteriorative reactions, such as powder stickiness and caking, lead to a decrease in the powder yield [6, 7], reduce the dryer performance [8], increasing the cost of energy and cleaning/disinfection operation [9, 10] and induce a loss of solubility which negatively impairs consumer acceptability [11]. Therefore, controlling water during the production and storage of dairy powders is crucial to avoid quality loss [1] and to reduce the production cost for the manufacturers [9].

In recent years, there has been a strong interest in the development of drying technologies such as spray drying. This technique has become the most widely used for the production of dairy powders thanks to its paramount advantages such as quickness, no direct contact with the matrix to be dried and ease of implementation [12]. The evaluation of the spray drying impact on the quality of the dairy product requires the knowledge of the physicochemical and compositional differences between the dairy matrices prior to drying [13]. Furthermore, this technological transformation also requires the understanding of the physical (e.g., glass transition and water sorption) and biochemical (e.g., protein denaturation) phenomena that govern the production and storage stability of dehydrated dairy products [14–16].

The understanding of the spray drying mechanism and its impact on the food matrix is the first step to ensure the technological transfer of this dehydration method from one product to another [1]. Several direct and indirect technical indicators were developed to evaluate the dairy powder quality. These indicators are evaluated according to international standardized methods. They constitute fundamental elements to predict the drying parameters, to characterize dairy powders (physicochemical, microbiological and rehydration properties) and to avoid problems due to glass transition, lactose crystallization and dryer fouling [17].

In this chapter, we will first review the classical manufacturing methodology of dairy powders. Secondly, we will provide some fundamental elements on dairy powder characteristics (i.e., the glassy state and the particle microstructure) followed by a discussion of some key indicators (e.g., sorption isotherm and glass transition temperature) to evaluate the quality of dairy powders. Finally, the production of camel milk powder will be reviewed as an example of the technological transfer of dairy powder production.

2. Dairy powders processing

2.1 Milk pretreatments

Before drying, several pretreatments can be applied to the milk and its derivatives (**Table 1**). During the last decades and as a result of technological progress, advanced techniques of membrane separation, purification, enzymatic transformation, demineralization, lactose-reducing, concentration and drying have initiated the appearance of some new dehydrated dairy products. These techniques provide different added values to dairy powders in relation to nutritional solutions for both humans and animals and techno-functional advantages in various foods or pharmaceutical formulations [1].

2.1.1 Membrane separation

Membrane separations are considered as green technologies due to their low cost and energy consumption, high separation efficiency with a large range of particle

Pretreatments	Objectives	References
Heat treatments: Preheating, pasteurization	Inactivation of enzymes (e.g., lipases in whole milk), Inactivation and destruction of pathogenic bacteria	[18]
Skimming, fat standardization and homogenization:	Allow the production of milk powders with different fat contents	[19]
Concentration	• Increasing the viscosity and the dry matter content • Reduced energy consumption	[20]
Membrane separation and purification	Production of various milk protein fractions	[21]
Enzymatic treatment	Production of lactose-free milk	[22]
Pre-crystallization of lactose	Reduce the hygroscopicity of powders	[23]
Formulation	• Maltodextrin: preventing sticking and caking of milk powders • Lecithin: instantaneous powder production	[24, 25]

Table 1.
Milk pretreatments.

sizes, preservation of nutritional and heat sensitive components as well as food properties and recovery of valuable components from dairy wastes [26]. Therefore, they became widely used in the production process of various dairy powders. Techniques such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) were utilized for various purposes including concentration, fractionation of dairy ingredients, adjustment of product content and reduction of the microbial load before the drying process.

Membrane filtration can be utilized for concentration of dairy products before drying [27]. In the case of whey powder production, membrane filtration can be used for whey concentration [28]. After being pasteurized, the whey is passed through a membrane filtration unit (usually NF) for partial ion removal, deacidification, and concentration to obtain whey solution with nearly 15 to 20% (w/v) of total solids content. Afterward, whey can be further concentrated with other techniques and processed to obtain powdered products [29]. Ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF) can also be used for milk concentration. They offer the advantages of cost reduction and the possibility to standardize and control the levels of proteins and lactose in dairy powders [30].

Before transforming them into powder, various dairy ingredients can be separated from milk and its byproducts such as whey and buttermilk, using membrane technology, including UF, MF and NF. The UF can be used for the recovery of lactose from whey before its transformation into powder [31]. De Souza et al. [32] used MF, UF, ion exchange, RO and spray-drying for the efficient recovery (74%) and purification of lactose from whey (99.8%). Furthermore, membrane techniques such as UF can be used for the recovery of whey proteins before their transformation into powder. Additionally, membrane filtration techniques can be used to produce high-protein dairy powders [33]. Prior to drying, skim milk produced directly after cream separation can be passed through a series of membrane filtration stages. Firstly, MF (≥1 μm) can be used to eliminate microorganisms or remaining fat, followed by ultrafiltration to keep micellar casein and whey proteins [34]. Wedel et al. [35] reported also the possibility of using UF to eliminate microbial cells and spores before drying in order to obtain low-microorganism dairy powders.

2.1.2 Lactose crystallization

After concentration and prior to the drying step, lactose crystallization in dairy products is very important in order to decrease caking and enhance powder quality [29]. The crystallized form of lactose is more stable during the drying process, and it gives less hygroscopic powder with better yield and physical stability [36]. Crystallization of lactose is crucial before drying, especially for products rich in lactose like whey powders [30]. This is supported by some research studies that demonstrated the importance of lactose crystallization in preventing dairy powder caking and stickiness [37].

Lactose crystallization consists of two steps which are nucleation and crystal growth [38]. During this process, a crystallization tank is used to transform lactose from the amorphous to the crystalline form which is less suitable to phase changes during drying at high temperatures and gives lesser sticky particles [29]. The concentrate is seeded with fine lactose crystals, which initiate crystallization by acting as nuclei [30]. Another reported method is the rapid crystallization of lactose in milk powders obtained after spray drying and before their storage in a fluidized bed dryer/crystallizer [39].

The effectiveness of lactose crystallization is highly affected by the composition and the mineral content of the product to be dried. In general, elevated mineral content such as calcium and high concentration of lactic acid can inhibit and retard lactose crystallization [40]. Therefore, it is very important to adjust the content of these components before drying using some techniques like membrane filtration. Other factors to be controlled include viscosity, pH, time, temperature, lactose crystal growth and nucleation, lactose supersaturation and crystallizer design [29].

2.1.3 Instantization

Single stage drying process of dairy products may generate dusty and non-instant powders that have high bulk density and bad rehydration properties. These problems can be solved through instantization which can reduce the bulk density and improve wettability and sinkability of particles to obtain dairy powders that can instantly be dissolved and well dispersed in cold water. Instantization can be generally realized through agglomeration and in some cases by combining agglomeration with lecithination (involves the addition of lecithin which is known for its surfactant properties to powders), especially for high-fat dairy powders [30]. Both instantization methods were tested for improving the physical and wettability properties of skim milk powders, and results showed that combining these two methods gave better results [41].

Agglomeration is the process of raising particle sizes of primary powders by bringing together individual particles to form a cluster-like structure in which the individual particles can still be distinguishable. This increase in particle size results in an increase in powder flowability. The structure of agglomerated particles is characterized by higher volumes of interstitial air in the form of pores and capillaries. This structure reduces the bulk density of powders and facilitates the penetration and movement of water throughout powders *via* capillary action during rehydration [33].

Agglomeration can be used for enhancing the rehydration properties such as wetting and physical properties such as flowability of dairy powders. It can ameliorate the properties of high-protein powders (whole milk, skim milk and fat-filled powders) as well as low-protein dairy powders (whey protein isolate powder, whey protein concentrate powder, casein-dominant powder, etc.) [42]. Agglomeration can be achieved through various techniques including spray dryer agglomeration, fluidized bed agglomeration, shear agglomeration, extrusion agglomeration, roller compaction agglomeration and steam jet agglomeration [33]. However, fluidized bed agglomeration remains the most commonly used agglomeration method for improving the physical and rehydration properties of dairy powders according to numerous studies.

2.1.4 Concentration

In most cases, milk and dairy products are concentrated up to 50–60% in total solids before being dried [17]. This step has several scientific, technological and economic advantages [20]. Indeed, concentration could limit bacterial multiplication by increasing the viscosity and the concentration of milk minerals as well as decreasing the water activity and the pH [20, 43]. In addition, this process induces an increase in powder particle size, which, consequently, impacts some physical properties of dairy powder such as density and powder flowability [44].

Besides, it was reported that the drying operation is expensive for powder manufacturers. The profitability of the drying operation is generally justified only for large production capacities ranging from 10×10^3 to 50×10^3 kg of raw milk per day [45]. Some authors found that concentration leads to a reduction in energy cost by a factor of 10–30 times of powder processing [46]. Currently, vacuum evaporation and reverse osmosis are two major concentration technologies commonly used in the dairy industry. A comparison of these two techniques is provided in **Table 2**. Depending on the specificities of the dairy matrix and the cost of the product, the manufacturer can use one of these two technologies.

2.2 Spray-drying

Drying operation consists of putting in contact a wet droplets with a hot and dry gas. This system assumes that a heat and mass exchange will be established between the two media. In most dryers, the ambient air is used as a dehydrating medium and acts as a carrier for the removed water. The main objective of the drying operation is to obtain a dairy powder with a reduced water content (3 to 5%, w/w) and a water activity (a_w) around 0.2 [49]. At this water activity, dairy powders become microbiologically and biochemically stable. Therfore, preventive measures should be put in place, especially for the control of relative humidity and temperature in the storage environment for milk powders. Generally, concentrated milk (55% total solids) is preheated again to a temperature of 45°C before drying. This preheating ensures the microbiological stability of the concentrated product [50], decreasing the viscosity of the concentrated product [18] and improving drying kinetics [51].

Several types of spray dryers are available to the manufacturers. These dryers are mainly classified according to the number of effects and stages as well as the atomization technology (centrifugal or pressure) [18], the mode of hot air entry (co-current, counter-current and mixed flow) and the geometry of the atomization chamber [45, 50].

Technology and principle	Advantages	Disadvantages	References
Reverse osmosis: Membrane filtration (porosity of 10–3 to 10–4 μm, with a pressure of 30–60 bar).	• Preserves the quality of the product. • Energy consumption 2 to 10 kWh/ton of water. • Operating temperature 10 to 60°C. • No water phase change. • Maximum total solids content: 20 to 25% (w/w).	• Rapid fouling of the membranes. • High installation and maintenance costs. • Limited nature of the products (10 to 12% dry matter and fat free).	[45, 47, 48]
Vacuum Evaporator: Boiling water in a partial vacuum.	• High evaporation capacity. • Energy and maintenance costs amortized (a minimum of three effects). • Operating temperature from 45 to 70°C. • Energy consumption 700/n kWh/ton of water (with 'n' number of effects). • Maximum total solids content: up to 60% (w/w).	• Risk of soiling and over-concentration. • High installation cost.	[17, 18, 20]

Table 2.
Comparison between concentration techniques.

3. Structural characteristics

3.1 Glassy state of dairy powders

Dairy products contain an important amount of lactose. In fact, lactose is a natural diholoside composed of a β-galactose molecule linked to either an α-glucose or β-glucose molecule *via* a β(1→4) glycosidic bond, resulting in α-lactose or β-lactose, respectively [52]. Depending on the used concentration process, the evolution of lactose state may differ. Indeed, in contrast to slow concentration (e.g., evaporation), the crystallization of lactose is limited by the time factor during spray-drying. Since the latter process is a very quick concentration process, the concentration of lactose increases rapidly without changing the physical state of the lactose. The resulting matrix then remains in an amorphous non-crystalline state called glassy or vitreous state [53, 54]. Indeed, a rapid elimination of water prevents the molecules from crystallizing and favors maintaining of their amorphous state.

In reality, the glassy state is a liquid state showing a solid-like behavior. In fact, a material in a glassy state behaves as a brittle solid (weakly ordered) with no crystalline structure and almost no molecular diffusion (less than 10^{-24} m^2 s^{-1} at 20°C) [54, 55]. This behavior is due to the low molecular mobility, which is a consequence of the very high viscosity of the dehydrated matrix (> 10^{12} $Pa.s^{-1}$ at 20°C) [23, 56, 57].

The vitreous state is a metastable state with relatively slow evolution which may last a long period of time [58]. In this state, molecules generally lose their translational mobility and only retain limited rotational and vibrational mobility. In this configuration, the molecules are thermodynamically unstable (non-equilibrium state) with high hygroscopicity [55, 59]. If the conditions of stability of the glassy state (temperature and/or humidity) are not respected, the molecules are likely to crystallize (most stable thermodynamic state) [56].

3.2 Structure and microstructure of a dairy powder particle

During drying, milk droplets lose moisture and solidify. The evolution of milk powder particles involves the formation of a cracked crust and vacuoles as a result of the evaporation of water. **Figure 1** shows the microstructure of milk powder containing different fat content. The spray-dried milk particles show a spherical shape, a collapsed structure (**Figure 1**) and a homogeneous wrinkled particle surface [60].

During the formation of the milk powder particle, a concentration gradient of the milk components is created. Two mechanisms are known to describe the transport of the components to the surface. In the first mechanism, surface-active compounds, mainly protein, adsorb easily at the air/water interface and migrate to the surface of the powder as the water is evaporated. In this case, fats, lactose and minerals are believed to be in the inner part of the particle [61]. Kim et al. proposed a second mechanism based on the solid/solute segregation system [62]. As water evaporates from the center of the particles to the surface, diffusion of solids (proteins, lipids, lactose and minerals) to the center of the particles is observed. As a result, the outer surface of the droplet becomes enriched with large molecules such as fat globules and proteins (casein micelles). The transport velocities of these components in the droplets during drying are strongly dependent on the concentration gradients and the values of their diffusion coefficients [63]. Gaiani et al. indicated that a combination of these two mechanisms is more likely possible. Indeed, during the first steps of drying, surface-active compounds migrate to the surface followed by the diffusion of solutes from the surface to the sprayed droplets inner part. This combination could have some limits that are linked to the drying kinetics as the surface could rapidly solidify and solutes migration could be stopped [64].

3.3 Dairy powder characterization

3.3.1 Moisture content and water activity

After drying, residual water can be detected in dairy powders and constitute their moisture content. However, the knowledge of the amount of this water is not

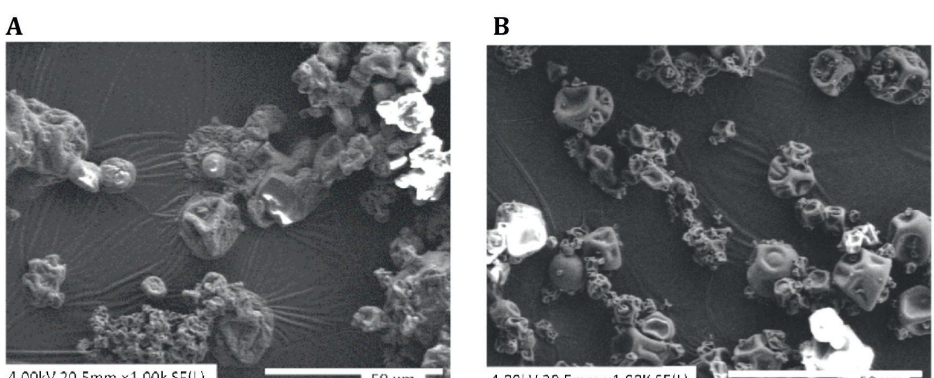

Figure 1.
Microstructure of a milk powder. (A) Particles of skim milk powder. (B) Particle of milk powder (27% of fat).

sufficient to assess the stability of dairy powders during storage. Indeed, a sufficient quantity of residual water can induce deteriorative physicochemical reactions and microbiological growth. The notion of water activity was developed to consider the interactions of water with the other components of the dehydrated matrix [65].

The moisture content as well as the water activity are strongly related to the thermodynamic properties of the drying air, especially its relative humidity [49]. In the case where the relative humidity of the drying air is not controlled, the amount of water in the powder can vary for the same drying temperatures. Understanding the enthalpic diagram of moist air called Mollier diagram, allows to choose the drying temperatures and predict the water activity of the milk powder produced. For good storage, water activity should be less than a critical water activity of 0.37 [57]. However, it is recommended to produce powder with a water activity of 0.2 for optimal conservation. At this water activity, the water content varies from 3 to 5% (w/w) depending on the nature of the dairy powders [21].

3.3.2 The sorption isotherm

Dairy powders are thermodynamically unstable. Indeed, they are generally hygroscopic and tend to adsorb moisture from storage air [57]. When the storage conditions are not respected, the water activity can drastically increase. Exceeding a critical activity, physical changes, such as lactose crystallization, could occur. To determine this critical activity, an accurate evaluation of the sorption isotherm for each produced dairy powder should be conducted. Indeed, the sorption isotherms are known to describe the equilibrium relationship (at constant temperature and pressure) between water content and water activity of food and dairy powders [66, 67]. The understanding of sorption isotherms can provide guidelines to control the drying process and to determine the storage conditions through the analysis of the desorption isotherm and adsorption isotherm, respectively [1].

Several factors could influence the adsorption of water by dairy powders (**Table 3**) and, consequently, the adsorption isotherms. These isotherms are described as a sigmoid curve showing a breaking point (**Figure 2**) corresponding to the apparent conditions of lactose crystallization [71]. This phenomenon occurs at a water activity

	Factors	References
Water adsorption	The quantity and hydrophobicity of proteins	[14, 68]
	The quantity and nature of minerals	[15]
	The quantity as well as the biochemical (hydrolyzed or not)) and physical state of lactose (amorphous or crystalline)	[14, 67]
	The particle size and surface composition of milk powder particles	[69]
	Humidity, temperature and storage time	[70]
Glass transition temperature	Temperature and water dynamics during storage	[71]
	Matrix Composition: water content, protein content (quantity, size and hydrophobicity) and lipid content	[14, 72]
	Molecular weight of polymers: Tg increases with increasing molecular weight	[73]

Table 3.
Factors influence the adsorption of water and the glass transition temperature of dairy powders.

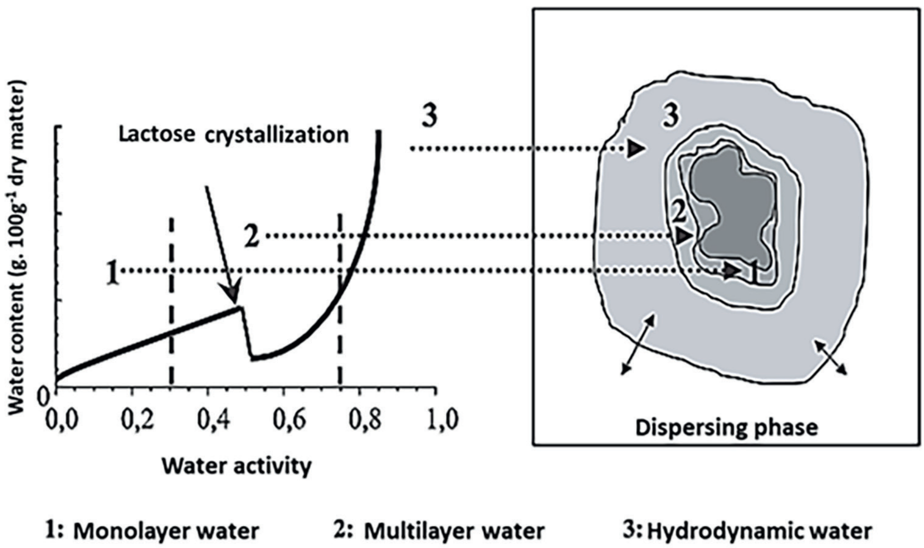

Figure 2.
Adsorption isotherm of a skimmed milk powder. Adapted from Shcuck et al., [52].

ranging from 0.37 to 0.7 and is characterized by a strong decrease in adsorbed water content following crystallization of amorphous lactose as α-lactose monohydrate [7, 68, 74]. Several authors have suggested dividing the adsorption isotherm of dairy powders into three distinct parts (**Figure 2**). In the first part, a gradual increase of water adsorption up to 0.2 to 0.3 of water activity (low moisture content) could be observed. The adsorbed water in this area is called monolayer moisture [75]. The proteins (caseins and serum proteins) are suggested to be the main water absorbers through water-protein interactions [68, 74]. In the second part, a quick increase of absorbed water is observed (up to 0.6 to 0.7 of water activity). A breaking point could occur as a consequence of a water release describing the change in physical state of the amorphous lactose, which absorbs water until crystallization [68, 76]. Beyond the breakpoint, water adsorption is resumed as milk minerals have a strong influence on water adsorption in this third part [53, 76].

3.3.3 The glass transition temperature

The glass transition is a key concept in food polymer science, and it can be affected by several factors (**Table 3**). The glass transition is considered as a second-order reaction during which state changes could occur, resulting in an important physical alteration of food powders. Indeed, during the glass transition, the system characteristics shifted from the glassy to the rubbery state, during which the matrix lose its viscosity. Such transition is essentially accompanied by two types of changes in physical properties. These changes are related to the rearrangement of the internal structure of amorphous molecules, leading to the modification of the rheological properties (viscoelastic modulus) and the thermodynamic properties (enthalpic relaxation, thermal capacity and coefficient of expansion) [57, 77, 78].

The most important parameter in this concept is the glass transition temperature (Tg). Knowledge of Tg is essential to describe the properties of a material because of its good correlation with its structural and thermodynamic properties [3, 78].

However, it was assumed that the glass transition takes place over a temperature range with an onset Tg (Tg_{onset}), a midpoint Tg ($Tg_{midpoint}$) and an offset Tg (Tg_{offset}). The range between Tg_{onset} and Tg_{offset} can vary from 10 to 20°C for amorphous sugars (e.g., lactose) and up to 50°C for high molecular weight polymers [55, 79]. The $Tg_{midpoint}$ is considered as the main glass transition temperature (Tg), which is specific for each material [51].

In the lactose/protein matrix (e.g., dairy powders), the glass transition temperature is relatively dominated by the physicochemical properties of lactose. Indeed, at the same water activity, dairy powders have a glass transition temperature approximately equal to that of a lactose-water mixture [7, 68]. At a temperature below Tg, the glass transition in dairy powders can be affected by the presence of water. In fact, water is considered as the main plasticizer in dairy powders. The glass transition temperature of pure lactose is equal to 101°C. At 10% water (pure lactose) or 5% (in milk powder), the Tg of lactose decreases to about 30°C. The water plasticization phenomena can be assessed by measuring the glass transition temperature. Indeed, a decrease in the Tg of hydrophilic molecules is observed as the water activity of the powder increases [59, 80, 81].

In dairy powders, the plasticizing effect of water only concerns lactose or its mixtures with proteins [82]. Approaching a critical water activity, water plasticization results in the softening of the dairy powder, followed by lactose crystallization [53, 68]. Indeed, it was demonstrated that the plasticizing effect of water particularly affects the thermal properties and structural resistance (α-relaxation) of lactose [68, 72]. An increase in water content reinforces the interactions of lactose with water through strong hydrogen bonds. Such interactions lead to an increase in lactose mobility, which results in a decrease in dairy powder's viscosity [59, 77, 83].

It is then important to control the glass transition temperature to avoid certain alteration reactions (**Table 4**) which are initiated depending on the difference between the storage temperature and the glass transition temperature. These reactions lead to a decrease in the shelf life and loss of quality of dairy powders [54, 58].

3.4 Physicochemical characterization

3.4.1 Whey protein denaturation (WPNI)

Several researchers have developed protein quality indicators such as the Whey Protein Nitrogen Index (WPNI) [50, 87]. The accuracy of this indicator can be influenced by several factors such as the feed nature [4], the equipment design [15] and the protein composition and quantity of the dairy product before drying [15, 88]. Indeed,

Consequences	References
Lactose crystallization and water release	[71, 84]
Powder Stickiness on dryer wall	[9]
Powder caking and flow difficulty	[3]
Initiation of the Maillard reaction	[85]
Fat oxidation	[86]

Table 4.
Main consequences of glass transition.

the protein fraction of milk is almost composed of 80% caseins and 20% of whey proteins. It is widely known that the latter protein group was the most sensitive to technological treatments, especially thermal operations, even for a short period of exposure. In fact, during heat treatment (> 60°C), whey proteins are firstly denatured and then irreversibly aggregate, leading to the formation of insoluble precipitates [89, 90].

The production of dairy powder includes a set of heat treatment operations that can modify the quality of milk proteins such as pasteurization and drying [15, 91, 92]. Thus, whey protein denaturation can be used as an indicator of the intensity of the drying process through the assessment of the WPNI [20], allowing the manufacturer to classify their dairy powders (**Table 5**). However, this indicator is mainly based on the loss of cow β-lactoglobulin [95], which may mislead the WPNI results for other milk obtained from other breeds that lack β-lactoglobulin.

3.4.2 Surface free fat content

Fats in dairy powders could exist in the free form at the particle surface (the outer surface and the vacuoles, pores and cracks surfaces) [18, 96]. In most cases, a high surface-free fat content SFC in dairy powders is not desired, except in the chocolate industry [97]. Indeed, SFC is often considered as an indicator of fat instability [98]. A high free fat content enhances the fat oxidation in milk powder [18] and changes in the color of the powder [86]. Moreover, fats at the powder surface increase the wetting time [99, 100] and affect the flowability of the powder [101, 102].

3.4.3 Powder densities, flowability, and particle size distribution

One of the main objectives of dairy powders production is to facilitate the handling and to reduce the transportation cost of some dairy products. Moreover, certain powder characteristics, such as flowability and rehydration, are strongly influenced by the density of the dairy powders [18, 20].

To achieve these goals, dairy powders should have a high density [4, 87]. Density is a complex characteristic and is influenced by several factors including the composition, the viscosity and the foam-ability of the concentrate before drying [20]. After drying, the particle size, the amount of occluded and interstitial air [50], the particle shape of the milk powder [4], and the physical state of lactose (amorphous or crystalline) [18] are also involved in determining the powder density.

<table>
<tr><th>Class</th><th>WPNI (g N_2. kg^{-1})</th><th>Examples of application</th></tr>
<tr><td>Extra low-heated powders</td><td>> 8.0</td><td rowspan="2">• Reconstitution and standardization of dairy products
• Ingredient in ice cream production
• Fortification of cheese and yogurt</td></tr>
<tr><td>Low heated powders</td><td>6 à 7.99</td></tr>
<tr><td>Medium heated powders</td><td>4.5–5.99</td><td>Chocolate and confectionery</td></tr>
<tr><td>Medium-high heated powders</td><td>1.51–4.49</td><td>Reconstituted condensed milk</td></tr>
<tr><td>High heated powders</td><td>< 1.5</td><td>Ingredient in bakery products</td></tr>
</table>

Table 5.
Thermal classification of dairy powders and their potential applications [15, 18, 93, 94].

Flowability	Carr's Index (%)	Hausner Ratio
Excellent	0–10	1.00–1.11
Good	11–15	1.12–1.18
Acceptable	16–20	1.19–1.25
Passable	21–25	1.26–1.34
Low	26–31	1.35–1.45
Very low	32–37	1.46–1.59
Extremely low	> 38	> 1.60

Table 6.
Classification of powders according to their flow index [103].

The powder flowability is a complex measurement that describes the ability of dairy powders to move freely during handling. The flowability is often influenced by the lactose crystallization level, the caking of the powder [3], the surface free fat content [4] as well as the shape and the size distribution of the particles [18]. The particle size distribution is an important characteristic of dairy powder quality. This parameter is mainly influenced by the drying method, the concentration and viscosity of the concentrate as well as the droplet size before drying [20]. Some indicators, such as Carr's index (compressibility index) and Haussner's ratio, have been proposed to classify powders based on their flowability (**Table 6**).

3.4.4 Rehydration properties

Rehydration describes the process of reconstituting the powder in water and is considered as the key characteristic for subsequent use of all food powders. This process is generally evaluated by the measurement of the insolubility, the wettability and the dispersibility indexes [20].

The insolubility index reflects the denaturation of proteins and the formation of insoluble complexes [104, 105], while the ability of the powder to be wetted by water without stirring is evaluated through the determination of the wettability index. Generally, a powder with high wettability has a wettability time of less than 3 min [17]. The dispersibility index describes the ability of the powder to disperse and disintegrate in water. This parameter is a good indicator of the instantaneity of milk powder [20]. A dispersible powder has a dispersibility index greater than 90% for skim milk powder and 85% for whole milk powder.

4. Camel milk powder production

Camel milk is one of the primary food stuff for nomads in arid and semi-arid regions. In traditional pharmacopeias, this milk is described for its nutritional and medicinal properties. Nowadays, the trading of raw or frozen camel milk is considered as an emergent international business. However, the transport and freezing operations are very expensive.

To overcome these problems, converting camel milk into powder could represent a valuable solution as it is already done for cow milk. However, such transformation could be very challenging due to the composition and the physiochemical of this milk. Actually, the physicochemical analysis of camel milk shows that the protein and lactose amounts are likely identical to cow milk with slightly higher ash content. However, the protein composition was totally different. Indeed, analysis of camel milk proteins showed higher β-casein (47%) and lower k-casein (3.5%) content [13]. The particularity of camel milk whey is the lack of β-Lactoglobulin and the overexpression of α-lactalbumin. Such protein composition may impair the powder particle formation and the transport of these compounds to the particle surface, which may change the powder properties [106].

Studies on the production of camel milk powder indicated that camel milk exhibited similar thermodynamic behavior during drying compared to cow milk. Overall, camel milk powder presented a higher bulk density than cow milk, showing comparable solubility [107]. Besides, it was indicated that camel milk proteins showed better thermal stability during drying. This stability is mainly due to the absence of β-lactoglobulin and the low initial content of free thiol (SH) groups [13]. Analysis of Scanning electron microscope (SEM) and Confocal Laser Scanning Microscopy (CLSM) micrographs of camel milk powder particles showed a spherical shrinked structure with relatively high fat and lactose content at their surface. The analysis of adsorption isotherms and glass transition temperature shows that beyond the glass transition, lactose in camel milk was less stable against crystallization. Lactose in camel milk completely crystallized at a critical water activity of 0.60 at a temperature of 25°C (instead of 0.70 for cow milk powder). This low stability was linked to the exposure of a high lactose content on the surface of camel milk powder particles [13]. However, analysis of moisture sorption isotherm indicated that at low water activity, camel milk powder showed a better storage ability when the glass transition conditions are respected [106, 108].

5. Conclusion

Milk and its derivatives are water-rich products which makes them perishable with very shorts shelf life. To solve such problem, dairy products generally undergoes stabilization treatments such as drying. Several drying methods have been developed for the production of dairy powders especially the spray drying. This technique allows rapid evaporation of water and the production of a stable powder for a long storage period (up to 2 years). However, maintaining this stability is a critical step and need to be evaluated. Several indicators have been proposed to assess the quality of dairy powders. Most of these indicators are likely related to water dynamics and its relationship with the stability of dairy powders. Indeed, water influences directly or indirectly the speed of physical and biochemical alterations. Currently, the available knowledge of milk transformation is generally derived from the processing of cow's milk. The transfer of this knowledge to other types of milk such as camel milk constitutes, in most cases, a scientific and industrial challenge. This chapter offers a guideline to characterize dairy powders through the understanding of the basics of dairy powder production and characterization.

Author details

Ahmed Zouari[1,2]*, Mondher Mzoughi[3] and Mohamed Ali Ayadi[1,4]

1 Valuation, Security and Food Analysis Laboratory, National Engineering School of Sfax, Sfax University, Tunisia

2 Biological engineering department, University Institute of Technology of Saint-Brieuc (IUT Saint-Brieuc), University of Rennes, Saint-Brieuc, France

3 Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Istanbul Technical University, Maslak, Istanbul, Türkiye

4 Laboratory of Quality and Safety of Agro-food Products, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium

*Address all correspondence to: ahmedzouarri@gmail.com

References

[1] Schuck P, Ouest A. Dairy Powders. Handbook of Food Powders. Cambridge, United States: Woodhead Publishing Limited; 2013. 437-464 p

[2] Silalai N, Roos YH. Roles of water and solids composition in the control of glass transition and stickiness of milk powders. Journal of Food Science. 2010;**75**(5):285-296

[3] Fitzpatrick JJ, Hodnett M, Twomey M, Cerqueira PSM, O'Flynn J, Roos YH. Glass transition and the flowability and caking of powders containing amorphous lactose. Powder Technology. 2007;**178**(2):119-128

[4] Augustin MA, Clarke PT, Craven H. Powdered milk. In: Characteristics of Milk Powders. Encyclopedia of Food Sciences and Nutrition. 2nd ed. Oxford, England: Academic Press; 2003. pp. 4703-4711

[5] Gianfrancesco A, Casteran C, Andrieux JC, Giardiello MI, Vuataz G. Assessment of physical characteristics and dissolution behavior of protein based powders. Procedia Food Science. 2011;**1**(Icef 11):601-607

[6] Fitzpatrick J. Powder properties in food production systems. In: Handbook of Food Powders. Cambridge, United States: Woodhead Publishing Limited; 2013. pp. 285-308

[7] Shrestha AK, Howes T, Adhikari BP, Bhandari BR. Water sorption and glass transition properties of spray dried lactose hydrolysed skim milk powder. LWT-Food Science and Technology. 2007;**40**:1593-1600

[8] Maury M, Murphy K, Kumar S, Shi L, Lee G. Effects of process variables on the powder yield of spray-dried trehalose on a laboratory spray-dryer. European Journal of Pharmaceutics and Biopharmaceutics. 2005;**59**(3):565-573

[9] Ozmen L, Langrish TAG. An experimental investigation of the wall deposition of milk powder in a pilot-scale spray dryer. Drying Technology. 2003;**21**(7):1253-1272

[10] Keshani S, Daud WRW, Nourouzi MM, Namvar F, Ghasemi M. Spray drying: An overview on wall deposition, process and modeling. Journal of Food Engineering. 2015;**146**:152-162

[11] Foster KD, Bronlund JE, Paterson AHJT. The contribution of milk fat towards the caking of dairy powders. International Dairy Journal. 2005;**15**(1):85-91

[12] Schuck P, Jeantet R, Bhandari B, Chen XD, Tuler Í, De Carvalho AF, et al. Recent advances in spray drying relevant to the dairy industry: A comprehensive critical review. Drying Technology. 2016;**3937**:1773-1790

[13] Zouari A, Briard-Bion V, Schuck P, Gaucheron F, Delaplace G, Attia H, et al. Changes in physical and biochemical properties of spray dried camel and bovine milk powders. LWT. 2020;**128**:109437

[14] Maidannyk VA, Roos YH. Water sorption, glass transition and "strength" of lactose – Whey protein systems. Food Hydrocolloids. 2017;**70**:76-87

[15] Schuck P. Effect of drying on milk proteins. In: Milk Proteins. 2nd ed. Cambridge, United States: Elsevier Inc.; 2014. 319-342 p

[16] Kelly GM, O'Mahony JA, Kelly AL, Huppertz T, Kennedy D, O'Callaghan DJ. Influence of protein concentration on surface composition and physico-chemical properties of spray-dried milk protein concentrate powders. International Dairy Journal. 2016;**52**:125

[17] Schuck P, Jeantet R, Dolivet A. Analytical Methods for Food and Dairy Powders. Hoboken, New Jersey: John Wiley & Sons; 2012

[18] Kelly AL, O'connell JE, Fox PF. Manufacture and properties of milk powders. In: Advanced Dairy Chemistry—1 Proteins: Part A/Part B. Boston, MA: Springer US; 2003. pp. 1027-1061

[19] Pugliese A, Cabassi G, Chiavaro E, Paciulli M, Carini E, Mucchetti G. Physical characterization of whole and skim dried milk powders. Journal of Food Science and Technology. 2017;**54**(11):3433-3442

[20] Schuck P. Modifications des propriétés fonctionnelles des poudres de protéines laitières: Impact de la concentration et du séchage. Innovations Agronomiques. 2011;**13**:71-99

[21] Schuck P, Mejean S, Dolivet A, Jeantet R, Bhandari B. Keeping quality of dairy ingredients. Le Lait. 2007;**87**:481-488

[22] Fialho TL, Martins E, Silveira ACP, de Silva CRJ, Perrone ÍT, Schuck P, et al. Lactose hydrolyzed milk powder: Thermodynamic characterization of the drying process. Drying Technology. 2018;**36**(8):922-931

[23] Langrish T, Wang EHL. Crystallization of powders of spray-dried lactose, skim milk and lactose-salt mixtures. International Journal of Food Engineering. 2006;**2**(4):1-15

[24] Silalai N, Roos YH. Mechanical relaxation times as indicators of stickiness in skim milk-maltodextrin solids systems. Journal of Food Engineering [Internet]. 2011;**106**(4):306-317

[25] Hammes MV, Englert AH, Noreña CPZ, Cardozo NSM. Study of the influence of soy lecithin addition on the wettability of buffalo milk powder obtained by spray drying. Powder Technology [Internet]. 2015;**277**:237-243

[26] Trung Le T, Cabaltica AD, Mien BV. Membrane separations in dairy processing. Journal of Food Research and Technology. 2014;**2**(1):1-14

[27] Moejes SN, van Boxtel AJB. Energy saving potential of emerging technologies in milk powder production. Trends in Food Science and Technology. 2017;**60**:31-42

[28] Schuck P. Dairy powders. In: Handbook of Food Powders: Processes and Properties. Cambridge, United States: Woodhead Publishing Limited; 2013. 437-464 p

[29] Ozel B, McClements DJ, Arikan C, Kaner O, Oztop MH. Challenges in dried whey powder production: Quality problems. Food Research International. 2022;**160**:111682

[30] McSweeney PLH, O'Mahony JA. Advanced dairy chemistry. In: Proteins: Applied Aspects. 4th ed. Vol. 1B. New York, United States: Springer; 2016. 1-498 pp

[31] Kravtsov VA, Kulikova IK, Anisimov GS, Evdokimov IA, Khramtsov AG. Variety of dairy ultrafiltration permeates and their purification in lactose production. IOP Conference Series: Earth and Environmental Science. 2021;**677**(3):1-16

[32] De Souza RR, Bergamasco R, da Costa SC, Feng X, Faria SHB, Gimenes ML. Recovery and purification of lactose from whey. Chemical Engineering and Processing: Process Intensification. 2010;**49**(11):1137-1143

[33] Hazlett R, Schmidmeier C, O'Mahony JA. Approaches for improving the flowability of high-protein dairy powders post spray drying – A review. Powder Technology. 2021;**388**:26-40

[34] Bista A, McCarthy N, O'Donnell CP, O'Shea N. Key parameters and strategies to control milk concentrate viscosity in milk powder manufacture. International Dairy Journal. 2021;**121**:105120

[35] Wedel C, Atamer Z, Dettling A, Wenning M, Scherer S, Hinrichs J. Towards low-spore milk powders: A review on microbiological challenges of dairy powder production with focus on aerobic mesophilic and thermophilic spores. International Dairy Journal. 2022;**126**:126

[36] Oliveira D, Fox P, O'Mahony JA. Byproducts from dairy processing. Byproducts from agriculture and fisheries: Adding value for food, feed. Pharma and Fuels. 2019;**14**:57-106

[37] Li R, Roos YH, Miao S. Influence of pre-crystallisation and water plasticization on flow properties of lactose/WPI solids systems. Powder Technology. 2016;**294**:365-372

[38] Huppertz T, Gazi I. Lactose in dairy ingredients: Effect on processing and storage stability. Journal of Dairy Science. 2016;**99**(8):6842-6851

[39] Yazdanpanah N, Langrish TAG. Fast crystallization of lactose and milk powder in fluidized bed dryer/crystallizer. Dairy Science & Technology. 2011;**91**(3):323-340

[40] Chandrapala J, Wijayasinghe R, Vasiljevic T. Lactose crystallization as affected by presence of lactic acid and calcium in model lactose systems. Journal of Food Engineering. 2016;**178**:181-189

[41] Hailu Y, Maidannyk VA, Murphy EG, McCarthy NA. Improving the physical and wettability properties of skim milk powders through agglomeration and lecithination. Journal of Food Engineering. 2023;**357**:111597

[42] McSweeney DJ, O'Mahony JA, McCarthy NA. Strategies to enhance the rehydration performance of micellar casein-dominant dairy powders. International Dairy Journal. 2021;**122**:105116

[43] Oliveira MN, Penna ALB, Nevarez HG. Production of evaporated milk, sweetened condensed milk and 'Dulce de Leche'. In: Tamime AY, editor. Dairy Powders and Concentrated Products. Oxford: Blackwell Publishing; 2009. pp. 149-180

[44] Crowley SV, Gazi I, Kelly AL, Huppertz T, O'Mahony JA. Influence of protein concentration on the physical characteristics and flow properties of milk protein concentrate powders. Journal of Food Engineering. 2014;**135**:31-38

[45] Caric M, Milanovic S, Akkerman C, Kentish SE, Tamime AY, Tamime A. Technology of evaporators, membrane processing and dryers. In: Dairy Powders & Concentrated Products. Chichester, UK: Wiley VCH; 2009. pp. 99-148

[46] Schuck P, Jeantet R, Tanguy G, Méjean S, Gac A, Lefebvre T, et al. Energy consumption in the processing of dairy and feed powders by evaporation and drying. Drying Technology. 2015;**33**(2):176-184

[47] Syrios A, Faka M, Grandison AS, Lewis MJ. A comparison of reverse osmosis , nanofiltration and ultrafiltration as concentration processes for skim milk prior to drying. International Journal of Dairy Technology. 2011;**64**(4):467-472

[48] Balde A, Aïder M. Effect of cryoconcentration, reverse osmosis and vacuum evaporation as concentration step of skim milk prior to drying on the powder properties. Powder Technology. 2017;**319**:463-471

[49] Schuck P, Dolivet A, Méjean S, Jeantet R. Relative humidity of outlet air: The key parameter to optimize moisture content and water activity of dairy powders. Dairy Science & Technology. 2008;**88**(1):45-52

[50] Westergaard V. Milk Powder Technology: Evaporation and Spray Drying. Soeborg, Denmark: Niro A/S; 2004

[51] Woo MW. Spray drying for food powder production [Internet]. In: Handbook of Food Powder. Cambridge, United States: Woodhead Publishing Limited; 2013. pp. 57-84

[52] Schuck P, Bouhallab S, Durupt D, Vareille P, Humbert JP, Marin M. Séchage des lactosérums et dérivés: rôle du lactose et de la dynamique de l'eau. Le Lait. 2004;**84**(3):243-268

[53] Roos YH. Water in dairy products. In: Roginski H, editor. Encyclopedia of Dairy Sciences Elsevier. Oxford: Academic Press; 2002. pp. 2727-2734

[54] Walstra P, Walstra P, Wouters JTM, Geurts TJ. Dairy Science and Technology. Boca Raton, Florida: CRC Press; 2005

[55] Carter BP, Schmidt SJ. Developments in glass transition determination in foods using moisture sorption isotherms. Food Chemistry. 2012;**132**(4):1693-1698

[56] Barbosa-Canovas G, Ortega-Rivas E, Juliano P, Hong Y. Food Powders. Physical Properties, Processing, and Functionality. New York, United States: Kluwer Academic/Plenum Publishers; 2005

[57] Roos YH. Importance of glass transition and water activity to spray drying and stability of dairy powders. Le Lait. 2002;**82**(4):475-484

[58] Roos YH. Water activity and glass transition. In: Water Activity in Foods: Fundamentals and Applications. Ames, IA: Blackwell Publishing; 2007. pp. 29-45

[59] Haque MK, Kawai K, Suzuki T. Glass transition and enthalpy relaxation of amorphous lactose glass. Carbohydrate Research. 14 Aug 2006;**341**(11):1884-1889

[60] Fyfe K, Kravchuk O, Nguyen AV, Deeth H, Bhandari B. Influence of dryer type on surface characteristics of milk powders. Drying Technology. 2011;**29**(7):758-769

[61] Fäldt P, Bergenståhl B. The surface composition of spray-dried protein-lactose powders. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 1994;**90**(2-3):183-190

[62] Kim EHJ, Dong Chen X, Pearce D. On the mechanisms of surface formation and the surface compositions of industrial milk powders. Drying Technology [Internet]. 2003;**21**(2):265-278

[63] Kim EHJ, Chen XD, Pearce D. Surface composition of industrial spray-dried milk powders. 1. Development of surface composition

during manufacture. Journal of Food Engineering. 2009;**94**(2):163-168

[64] Gaiani C, Morand M, Sanchez C, Tehrany EA, Jacquot M, Schuck P, et al. How surface composition of high milk proteins powders is influenced by spray-drying temperature. Colloids and Surfaces. B, Biointerfaces. 2010;**75**:377-384

[65] Hardy J, Scher J, Banon S. Water activity and hydration of dairy powders. Le Lait. 2002;**82**(4):441-452

[66] Abdenouri N, Idlimam A, Kouhila M. Sorption isotherms and thermodynamic properties of powdered milk. Chemical Engineering Communications. 2010;**197**(8):1109-1125

[67] Sheokand S, Modi SR, Bansal AK. Dynamic vapor sorption as a tool for characterization and quantification of amorphous content in predominantly crystalline materials. Journal of Pharmaceutical Sciences. 2014;**103**(11):3364-3376

[68] Haque MK, Roos YH. Water sorption and plasticization behavior of spray-dried lactose/protein mixtures. Journal of Food Science: Food Engineeering and Physical Properties. 2004;**69**(8):384-391

[69] Murrieta-Pazos I, Gaiani C, Galet L, Cuq B, Desobry S, Scher J. Comparative study of particle structure evolution during water sorption: Skim and whole milk powders. Colloids and Surfaces. B, Biointerfaces. 2011;**87**(1):1-10

[70] Langová J, Štencl J. Moisture sorption isotherms of whole milk powder in the temperature range of 5-35 °C and critical values of water activity prediction. Acta Veterinaria Brno. 2014;**83**:S35-S40

[71] Jouppila K, Roos YH. Glass transitions and crystallization in milk powders. Journal of Dairy Science. 1994;**77**(10):2907-2915

[72] Fan F, Roos YH. Crystallization and structural relaxation times in structural strength analysis of amorphous sugar/whey protein systems. Food Hydrocolloids. 2016;**60**:85-97

[73] Roos Y, Karel M. Plasticizing effect of water on thermal behavior and crystallization of amorphous food models. Journal of Food Science. 1991;**56**(1):38-43

[74] Foster KD, Bronlund JE, Paterson AHJ. The prediction of moisture sorption isotherms for dairy powders. International Dairy Journal. 2005;**15**(4):411-418

[75] Berlin E, Anderson BA, Pallansch MJ. Water vapor sorption properties of various dried milks and Wheys. Journal of Dairy Science. 1968;**51**(9):1339-1344

[76] Pısecký J. Handbook of milk powder manufacture. Niro A/S, Copenhagen. 1997;**3**(1):1-3

[77] Hogan SA, Famelart MH, O'Callaghan DJ, Schuck P. A novel technique for determining glass–rubber transition in dairy powders. Journal of Food Engineering. 2010;**99**(1):76-82

[78] Liu Y, Bhandari B, Zhou W. Glass transition and enthalpy relaxation of amorphous FoodSaccharides: A review. Journal of Agricultural and Food Chemistry. 2012:5701-5717

[79] Schmidt SJ. Water and solids mobility in foods. Advances in Food and Nutrition Research. 2004;**48**:1-103

[80] Roos Y. Solid and liquid states of lactose. In: Advanced Dairy Chemistry. New York, United States: Springer; 2009. pp. 17-33

[81] Sablani SS, Kasapis S, Rahman MS. Evaluating water activity and glass transition concepts for food stability. Journal of Food Engineering [Internet]. 2007;**78**(1):266-271

[82] Slade L, Levine H, Reid DS. Beyond water activity: Recent advances based on an alternative approach to the assessment of food quality and safety. Critical Reviews in Food Science and Nutrition. 1991;**30**(2-3):115-360

[83] Fan F, Mou T, Nurhadi B, Roos YH. Water sorption-induced crystallization, structural relaxations and strength analysis of relaxation times in amorphous lactose/whey protein systems. Journal of Food Engineering. 2017;**196**:150-158

[84] Roos YR, Karel MA. Crystallization of amorphous lactose. Journal of Food Science. May 1992;**57**(3):775-777

[85] Karmas R, Pilar Buera M, Karel M. Effect of glass transition on rates of nonenzymic browning in food systems. Journal of Agricultural and Food Chemistry. 1992;**40**(5):873-879

[86] Nielsen BR, Stapclteldt H, Skibsted LH. Differentiation between 15 whole milk powders in relation to oxidative stability during accelerated storage: Analysis of variance and canonical variable analysis. International Dairy Journal. 1997;**7**(8-9):589-599

[87] Schuck P. Dehydrated dairy products. Milk powder: Types and manufacture. In: Fuquay JW, editor. Encyclopedia of Dairy Sciences. 2nd ed. San Diego, CA: Academic Press; 2011. p. 108116

[88] Sikand V, Tong PS, Walker J. Impact of protein standardization of milk powder with lactose or permeate on whey protein nitrogen index and heat classification. Dairy Science & Technology. 2008;**88**(1):105-120

[89] Hawalkar VR, Kalab M. Thermal denaturation and aggregation of β-lactoglobulin at pH 2, 5. Effect of ionic strength and protein concentration. Milchwissenschaft. 1985;**40**(1):31-34

[90] Roefs SP, De Kruif KG. A model for the denaturation and aggregation of β-Lactoglobulin. European Journal of Biochemistry. 1994;**226**(3):883-889

[91] De la Fuente MA, Hemar Y, Tamehana M, Munro PA, Singh H. Process-induced changes in whey proteins during the manufacture of whey protein concentrates. International Dairy Journal. 2002;**12**(4):361-369

[92] Anema S, McKenna A. Reaction kinetics of thermal denaturation of whey proteins in heated reconstituted whole milk. Journal of Agricultural and Food Chemistry. 1971;**1996**(44):422-428

[93] Syll O, Richard B, Willart JF, Descamps M, Schuck P, Delaplace G, et al. Rehydration behaviour and ageing of dairy powders assessed by calorimetric measurements. Innovative Food Science & Emerging Technologies. 2012;**14**:139-145

[94] Sharma A, Jana AH, Chavan RS. Functionality of milk powders and milk-based powders for end use applications - A review. Comprehensive Reviews in Food Science and Food Safety. 2012;**11**(5):518-528

[95] O'Sullivan EA, Kelly PM, Fitzgerald RJ, O'Farrell K, Murphy MF, Harrington D. Effect of β-lactoglobulin phenotype on whey protein nitrogen index and sulphydryl content of skim milk powder. Le Lait. 1999;**79**(2):229-244

[96] Vignolles JR, Lopez C, Schuck P. Free fat, surface fat and dairy powders: Interactions between process

and product. A review. Le Lait. 2007;**87**:187-236

[97] Keogh K, Twomey M, O'kennedy B, Donal M. Effect of milk composition on spray-dried high-fat milk powders and their use in chocolate. Journal of Food Protection. 2009;**72**(10):2162-2169

[98] Vignolles ML, Lopez C, Madec MN, Ehrhardt JJ, Méjean S, Schuck P, et al. Fat properties during homogenization, spray-drying, and storage affect the physical properties of dairy powders. Journal of Dairy Science. 2009;**92**(1):58-70

[99] Crowley SV, Kelly AL, Schuck P, Jeantet R, O'Mahony JA. Rehydration and solubility characteristics of high-protein dairy powders. In: Advanced Dairy Chemistry. New York, United States: Springer; 2016. pp. 99-131

[100] Gaiani C, Ehrhardt JJ, Scher J, Hardy J, Desobry S, Banon S. Surface composition of dairy powders observed by X-ray photoelectron spectroscopy and effects on their rehydration properties. Colloids and Surfaces. B, Biointerfaces. 2006;**49**(1):71-78

[101] Hansen PS. Production of agglomerated fat-filled milk powder. International Journal of Dairy Technology. 1980;**33**(January):19-23

[102] Fitzpatrick JJ, Iqbal T, Delaney C, Twomey T, Keogh MK. Effect of powder properties and storage conditions on the flowability of milk powders with different fat contents. Journal of Food Engineering. 2004;**64**(4):435-444

[103] Lebrun P, Krier F, Mantanus J, Grohganz H, Yang M, Rozet E, et al. Design space approach in the optimization of the spray-drying process. European Journal of Pharmaceutics and Biopharmaceutics. 2012;**80**(1):226-234

[104] Corredig M, Dalgleish DG. The mechanisms of the heat-induced interaction of whey proteins with casein micelles in milk. International Dairy Journal. 1999;**9**(3-6):233-236

[105] Oldfield DJ, Taylor MW, Singh H. Effect of preheating and other process parameters on whey protein reactions during skim milk powder manufacture. International Dairy Journal. 2005;**15**(5):501-511

[106] Zouari A, Schuck P, Gaucheron F, Triki M, Delaplace G, Gauzelin-Gaiani C, et al. Microstructure and chemical composition of camel and cow milk powders' surface. LWT. 2020;**117**:108693

[107] Zouari A, Mtibaa I, Triki M, Jridi M, Zidi D, Attia H, et al. Effect of spray-drying parameters on the solubility and the bulk density of camel milk powder: A response surface methodology approach. International Journal of Dairy Technology. 2020:616-624. DOI: 10.1111/1471-0307.12690

[108] Deshwal GK, Singh AK, Kumar D, Sharma H. Effect of spray and freeze drying on physico-chemical, functional, moisture sorption and morphological characteristics of camel milk powder. LWT. 2020;**134**:110117