Effects of spray-drying conditions on the chemical, physical, and sensory properties of cheese powder

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ABSTRACT

Dairy powders are produced to increase the shelf life of fresh dairy products and for use as flavoring agents. In this study, 24 cheese powders produced under 7 different conditions were used to investigate the effects of spray-drying parameters (e.g., inlet air temperature, atomization pressure, and outlet air temperature) on the quality of white cheese powder. Composition, color, physical properties, reconstitution, and sensory characteristics of white cheese powders were determined. The results revealed that the white cheese powders produced in this study had low moisture content ratios and water activity values. High outlet air temperatures caused browning and enhanced Maillard reactions. Additionally, high outlet air temperatures increased wettability and dispersibility and decreased the solubility of white cheese powders. Free fat content was positively correlated with inlet air temperature and negatively correlated with outlet air temperature and atomization pressure. Sensory analyses revealed that white cheese powder samples had acceptable sensory characteristics with the exception of the sample produced at an outlet air temperature of 100°C, which had high scores for scorched flavor and color and low scores for cheese flavor.

Key words: spray drying, cheese powder, white cheese, powder characteristics

INTRODUCTION

Cheese is one of the most important dairy products with more than 1,000 different varieties (Fox, 2011). Dehydrated cheese (e.g., cheese powder) is usually used as a food ingredient to improve both the flavor and mouthfeel of food products (Fox et al., 2000; Guinee and Kilcawley, 2004; Guinee, 2011). Cheese powder is a promising product with increasing consumption worldwide (Guinee, 2011).

Several parameters are used to evaluate cheese powder quality. The composition of cheese powder provides useful information on its physical, structural, and morphological features (Kim et al., 2002; Fitzpatrick et al., 2004; Thomas et al., 2004; Barbosa-Canovas et al., 2005; Paterson et al., 2007; Vignolles et al., 2007). Free fat directly affects oxidation during storage and reconstitution of powders (Kelly et al., 2002; Kim et al., 2002, 2009a; Vignolles et al., 2007, 2009; Park et al., 2014). In addition, distribution of fat plays a role in flavor development and stability, because lipid oxidation is responsible for off-flavor formation and reduced shelf life (Park and Drake, 2014). Physical properties of cheese powders (e.g., color and density) are important parameters of quality; color indicates any defects during processing and storage. Although bulk and tapped densities of powders are used to assess storage, processing, packaging, and distribution conditions, particle density in tandem with bulk and tapped densities provide valuable information on particle properties and interactions (Barbosa-Canovas et al., 2005; Schuck, 2011). Factors that negatively affect flavor, color, or texture during processing and storage are of concern. Nonenzymatic browning (i.e., the Maillard reaction) is one of the main factors that cause the formation of chemically stable and nutritionally unavailable derivatives from dairy powders (Palombo et al., 1984; Kilic et al., 1997). Furthermore, most food additives prepared in powder form are hydrated before use. Therefore, interfacial properties, water interactions, and dissolution of dairy powders are important factors in food development and formulation (Thomas et al., 2004; Schuck, 2011; Richard et al., 2013). The reconstitution of dairy powders with water depends on several properties such as their wettability, sinkability, dispersibility, and solubility (Freudig et al., 1999; Schuck, 2011). In addition, sensory characteristics are important to achieve customer satisfaction.

Cheese powder production involves 4 main steps. First, the blend formulation is determined. The blend consists mainly of natural cheese, water, emulsifying salts, and different additives such as dairy ingredients (skim milk solids, whey, and lactose), starch, maltodex-

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trins, flavors, and flavor enhancers (enzyme-modified dairy ingredients, NaCl, monosodium glutamate, yeast extracts), antioxidants, and, sometimes, coloring agents. Second, the blend is heated to 75 to 85°C and sheared, resulting in a hot molten slurry. Third, homogenization may be performed at 15 and 5 MPa. Finally, the hot molten slurry is spray dried. In the production of cheese powder, the most important process is spray drying (Fox et al., 2000; Guinee and Kilcawley, 2004; Guinee, 2011; Varming et al., 2013).

Spray drying is a suspended-particle processing technique that has become the most important method for drying fluid foods (Filkova et al., 2006). The main food sector that uses spray driers is the dairy industry (Bhandari et al., 2008). The properties of dairy powders and the costs of dairy powder production are affected by the spray-drying process (Schuck, 2002; Vignolles et al., 2009; Erbay and Koca, 2012a).

Even though there is increasing demand for dairy powders and cheese powders, cheese powders are rarely described in the scientific literature (Kilic et al., 1997; Srinivasan et al., 2000; Varming et al., 2010, 2013; Erbay and Koca, 2015). One study focused on the effects of spray drying on the volatile compounds in cheese powder (Varming et al., 2011). The current study investigated the effects of spray drying on cheese powder quality.

MATERIALS AND METHODS

Materials

White cheese (previously ripened for 7 mo) was supplied by Sütaş Dairy Company (Bursa, Turkey). Water, fat, protein, ash, and salt contents of white cheese were 52.0, 24.4, 18.4, 4.9, and 4.3%, respectively. White cheese blocks were ground into small pieces, which were transferred to air- and water-tight durable polypropylene plastic containers, stored at 2°C, and processed within 48 h.

Before spray drying, a white cheese slurry consisting of ground white cheese, water, and 3% Joha emulsifying salts (Kipa Chemical Company, Istanbul, Turkey) was prepared. The slurry was heated by adding water at 80°C and sheared in a blender (model LB10S, Waring, Torrington, CT) at 6,000 rpm for 1 min. Subsequently, the slurry was heated in a water bath to 80°C and sheared again at 6,000 rpm for 10 min. The slurry (25% DM based on cheese) was transferred to a spray drier at 45°C.

Spray-Drying Procedure

The white cheese slurry was dried in a pilot-scale spray drier (Mobile Minor Niro-Atomizer, Soeborg,

Denmark). The schematic illustration of the spray drier was shown in a previous study (Erbay and Koca, 2012b). Cheese slurry (3.2 L for each batch) was pumped using a peristaltic pump (BT600-2J, Longer Precision Pump, Baoding, Hebei, China) into a rotary atomizer and atomized into a drying cabinet (1.2 m high × 0.87 m in diameter). The feed rate was adjusted based on the inlet and outlet drying air temperatures. The rotary atomizer was controlled by an air turbine wheel at 20,000 to 31,500 rpm. The atomizer wheel had a 50-mm diameter with 24 vanes to create a uniform atomization. The co-current airflow was 0.08 kg/s. Experiments were performed with an inlet air temperature of 160 to 230°C, an outlet air temperature of 60 to 100°C, and an atomization pressure of 294 to 588 kPa. The cheese powder samples were packaged in polyethylene terephthalate/aluminum/low-density polyethylene (PET/Al/LDPE) and analyzed within 48 h. To prevent cross-contamination between samples, the drying chamber was washed with detergent and hot water and then a run without sample was performed between samples.

White Cheese Powder Composition

Moisture, fat, and protein contents of white cheese powder samples were determined by gravimetric (IDF, 1982), Gerber (IDF, 1981), and Kjeldahl (AOAC International, 2000; method 991.20) methods, respectively. Ash and salt contents were determined by the gravimetric (AOAC International, 2000; method 930.30) and Mohr (IDF, 1988) methods, respectively. Titratable acidity was expressed as percent lactic acid (AOAC International, 2000; method 947.05); pH was measured with a pH meter.

Color Evaluation

Using a Hunter ColorFlex colorimeter (Hunter Associates Laboratory, Reston, VA), white cheese powder color was measured in terms of *L* (lightness), *a* (redness and greenness), and *b* (yellowness and blueness). A quartz 2.5-inch glass containing the cheese powder was placed above the light source and covered with an opaque cover. Then, *L*, *a*, and *b* values were recorded. Color differences (ΔE), chroma (color intensity), and browning index (*BI*) values were calculated as described previously (Askari et al., 2008):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}, \quad [1]$$

$$\text{Chroma} = \sqrt{a^2 + b^2}, \text{ and} \quad [2]$$

$$BI = \frac{100 \times \left[\frac{(a + 1.75 \times L)}{(5.645 \times L + a - 3.012 \times b)} \right]}{0.17} \quad [3]$$

Nonenzymatic Browning

The nonenzymatic browning degrees (NBD) of white cheese powder samples were measured by an enzymatic digestion method (Palombo et al., 1984; Kilic et al., 1997). The method was based on pronase proteolysis, which releases brown pigments. In this experiment, 1 g of white cheese powder was used. Sample absorbance was measured at 420 (A_{420}) and 550 (A_{550}) nm in a spectrophotometer (Cary 50 Bio UV-Visible Spectrophotometer, Varian, Palo Alto, CA). Optical density was calculated using the following equation:

$$OD = A_{420} - A_{550}, \quad [4]$$

and the NBD values for each sample were expressed as OD/g of DM.

Powder Density Determination

Bulk, tapped, and particle densities of white cheese powders were measured. Bulk density was measured by pouring white cheese powder to the 100-mL mark of a tared graduated cylinder and recording the weight (Jinapong et al., 2008). The measuring cylinder was tapped 200 times, and the volume was recorded to calculate the tapped density (Jinapong et al., 2008). Particle density was measured by the fluid displacement method in a 100-mL volume liquid pycnometer and with petroleum ether (Svarovsky, 1987; Barbosa-Canovas et al., 2005). All densities were expressed in kilograms per meter cubed.

Powder Reconstitution

Three properties of white cheese powder (wettability, dispersibility, solubility) were investigated to evaluate the overall reconstitution skills. Wettability was determined by the method described in GEA Niro (2005a) with some modifications. Briefly, 0.075 g of white cheese powder was added to 100 mL of distilled water at 35°C from a constant height, and the wetting time of the powder particles was observed. Dispersibility was determined by the method described by Jinapong et al. (2008), except that the sieve had a diameter of 500 μ m. Dissolubility was determined as the solubility index by Haenni method (Hawthorne, 1944; Erbay and Koca, 2015).

Free Fat Content

The free fat content of dairy powders is commonly quantified by the solvent extraction method (Vignolles et al., 2007). In this study, the modified solvent extraction method described in GEA Niro (2005b) was used. The results were expressed as percentage of free fat content.

Scanning Electron Microscopy

Cheese powder samples were attached to the double-sided adhesive carbon tabs mounted on scanning electron microscopy stubs, coated with gold, and examined under a Philips scanning electron microscope (Philips XL30, Eindhoven, the Netherlands) equipped with a back-scattered electron detector.

Water Activity

Water activity values of white cheese powder samples were measured with a water activity measurement probe (Testo, Freiburg, Germany).

Sensory Evaluation

The sensory properties of white cheese powder samples were determined using 10 trained panelists. Caking degree, color (browning degree), scorched flavor, foreign flavor, and cheese flavor were determined. A unipolar scale ranging from 1 (representing to none/absent) to 9 (representing to highest intensity) was used for each sensory property. To evaluate caking degree, color (browning degree), and scorched flavor, all panelists tried cheese powder samples cooked to different degrees. For cheese flavor, ripened white cheese was used as reference.

Experimental Design and Statistical Analyses

The experimental design, drying conditions, and production codes are shown in Table 1. The experiments were carried out at different inlet air temperatures (160, 195, and 230°C), outlet air temperatures (60, 80, and 100°C), and atomization pressures (294, 441, and 588 kPa). Two drying parameters were kept constant while the other parameter was changed. When the inlet and outlet drying air temperatures were 195 and 80°C (at the center), respectively, runs were carried out at atomization pressures of 294, 441, and 588 kPa. Similarly, when the atomization pressure and outlet drying air temperature were 441 kPa and 80°C (at the center), respectively, runs were carried out with inlet drying air temperatures of 160, 195, and 230°C. When the atomi-

Table 1. Spray-drying conditions used in the production of white cheese powder

Code	Inlet temperature (°C)	Atomization pressure (kPa)	Outlet temperature (°C)
1	160	441	80
2	195	441	80
3	230	441	80
4	195	441	60
5	195	441	100
6	195	294	80
7	195	588	80

zation pressure and inlet drying air temperature were 441 kPa and 195°C, respectively, runs were carried out with outlet temperatures of 60, 80, and 100°C.

Six production runs were performed at the second experimental point (center point of drying parameters) and 3 productions performed for all other experimental points (a total of 24 productions were made). The analyses were repeated 3 times. Statistical analyses were performed using SPSS version 13.0 (ver. 13.0 for Windows, SPSS Inc., Chicago, IL). Data were analyzed by ANOVA and Duncan post hoc test. Statistical significance was set at $P < 0.05$.

RESULTS AND DISCUSSION

In this study, we investigated the effects of spray-drying conditions (e.g., inlet and outlet air temperatures and atomization pressure) on properties of white cheese powder. The white cheese powder properties included powder composition (moisture, protein, fat, ash, and salt contents, titratable acidity, and pH), color values and nonenzymatic browning (L , a , b , ΔE , chroma, and NBD), physical properties (bulk, tapped, and particle densities, wettability, dispersibility, solubility index, free fat content, and water activity), and sensory characteristics (sensorial scorched, foreign and cheese flavors, caking, and color).

Effects on Powder Composition

The average composition of the white cheese powders produced at different spray-drying conditions is shown in Table 2. The average moisture, protein, fat, ash, and salt contents, titratable acidity, and pH values of cheese powder samples were 1.47 to 2.66%, 36.30 to 36.65%, 46.25 to 46.91%, 14.50 to 14.73%, 8.08 to 8.30%, 4.03 to 4.32%, and 5.41 to 5.57, respectively. We detected no significant differences in powder composition among the different spray-drying conditions. However, high outlet air temperatures contributed to a reduction in moisture ratio; this effect had no significant value because all moisture content values were $<3\%$.

Effects on Color Values and Nonenzymatic Browning

The color values (L , a , and b) of white cheese powder samples were measured to calculate ΔE , chroma, and BI. The color values of white cheese slurry and white cheese were used as references during the calculation of 2 different ΔE values. Moreover, nonenzymatic browning of white cheese powder samples was analyzed (Table 3). Inlet air temperature had no significant effect on white cheese powder color. However, atomization pressure increased color values. Additionally, outlet air temperature had dramatic effects on all color values. Although the color values fluctuated at outlet air temperatures of 60 to 80°C, a significant effect was obtained at 100°C. The increase in outlet air temperature increased a , b , ΔE (white cheese as reference), chroma, BI, and NBD ($P < 0.05$) and decreased L and ΔE (white cheese slurry used as reference). These results revealed that lightness decreased whereas redness and yellowness increased with increasing outlet air temperatures. This is a characteristic feature of browning, which was detected in both evaluation of nonenzymatic browning (Table 3) and sensory analyses. The Maillard reaction is induced by temperature, which is mostly attributed to the outlet air temperature in spray-drying processes. The thermal effects could be clearly observed at high outlet air temperatures, in accordance with other published reports (Hardy et al., 1999; Thomas et al., 2004).

The ΔE values calculated with different reference samples differed based on the spray-drying conditions. Those calculated using white cheese slurry as reference increased as the outlet air temperature increased; however, those calculated using white cheese as reference decreased with increasing outlet air temperatures. Moreover, the color of white cheese powder was similar to that of the white cheese slurry, which is whiter than white cheese. This color variation resulted from the processed cheese production step. The yellow color (b) of a food product is associated with its fat content and the size of fat globules dispersed in the solution or protein matrix. The smaller the fat globule size, the greater the effect of light scattering and the whiter the product. Homogenization of fat increases with the addition of emulsifying salts (McClements, 2005; Cunha and Viotto, 2010).

Effects on Physical Properties

Outlet air temperature had the greatest effect on the physical characteristics of white cheese powders (Table 4). Inlet and outlet air temperatures caused significant variations on bulk, tapped, and particle densities of the powders. White cheese powders produced at low inlet or outlet air temperatures had higher bulk, tapped,

Table 2. Variation in product composition with process conditions of spray drying (means $\pm$ SD)

Item	Inlet temperature		
	160°C	195°C	230°C
Moisture content (%)	1.75 $\pm$ 0.34 ^a	1.97 $\pm$ 0.31 ^a	1.56 $\pm$ 0.19 ^a
Protein (%)	36.65 $\pm$ 0.17 ^a	36.32 $\pm$ 0.25 ^a	36.44 $\pm$ 0.20 ^a
Fat (%)	46.58 $\pm$ 0.19 ^a	46.69 $\pm$ 0.00 ^a	46.80 $\pm$ 0.19 ^a
Ash (%)	14.50 $\pm$ 0.22 ^a	14.54 $\pm$ 0.14 ^a	14.52 $\pm$ 0.28 ^a
Salt (%)	8.21 $\pm$ 0.11 ^a	8.30 $\pm$ 0.04 ^a	8.24 $\pm$ 0.09 ^a
Titratable acidity (%)	4.29 $\pm$ 0.15 ^a	4.15 $\pm$ 0.28 ^a	4.13 $\pm$ 0.17 ^a
pH	5.44 $\pm$ 0.02 ^a	5.48 $\pm$ 0.03 ^b	5.52 $\pm$ 0.02 ^b
Item	Atomization pressure		
	294 kPa	441 kPa	588 kPa
Moisture content (%)	1.47 $\pm$ 0.19 ^a	1.97 $\pm$ 0.31 ^{ab}	2.33 $\pm$ 0.40 ^b
Protein (%)	36.42 $\pm$ 0.05 ^a	36.32 $\pm$ 0.25 ^a	36.44 $\pm$ 0.10 ^a
Fat (%)	46.69 $\pm$ 0.00 ^a	46.69 $\pm$ 0.00 ^a	46.91 $\pm$ 0.39 ^a
Ash (%)	14.73 $\pm$ 0.11 ^a	14.54 $\pm$ 0.14 ^a	14.60 $\pm$ 0.18 ^a
Salt (%)	8.19 $\pm$ 0.11 ^{ab}	8.30 $\pm$ 0.04 ^b	8.08 $\pm$ 0.16 ^a
Titratable acidity (%)	4.19 $\pm$ 0.10 ^a	4.15 $\pm$ 0.28 ^a	4.26 $\pm$ 0.18 ^a
pH	5.47 $\pm$ 0.02 ^b	5.48 $\pm$ 0.03 ^b	5.41 $\pm$ 0.04 ^a
Item	Outlet temperature		
	60°C	80°C	100°C
Moisture content (%)	2.66 $\pm$ 0.08 ^a	1.97 $\pm$ 0.31 ^b	1.73 $\pm$ 0.18 ^c
Protein (%)	36.30 $\pm$ 0.15 ^a	36.32 $\pm$ 0.25 ^a	36.50 $\pm$ 0.10 ^a
Fat (%)	46.25 $\pm$ 0.77 ^a	46.69 $\pm$ 0.00 ^a	46.69 $\pm$ 0.00 ^a
Ash (%)	14.66 $\pm$ 0.01 ^a	14.54 $\pm$ 0.14 ^a	14.63 $\pm$ 0.14 ^a
Salt (%)	8.26 $\pm$ 0.07 ^a	8.30 $\pm$ 0.04 ^a	8.16 $\pm$ 0.22 ^a
Titratable acidity (%)	4.03 $\pm$ 0.12 ^a	4.15 $\pm$ 0.28 ^a	4.32 $\pm$ 0.13 ^a
pH	5.57 $\pm$ 0.08 ^b	5.48 $\pm$ 0.03 ^a	5.50 $\pm$ 0.03 ^{ab}

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

and particle density values. In general, low outlet air temperatures contribute to uniform drying of droplets, controlled particle shrinkage, and higher density values (Kelly et al., 2002). However, higher inlet air temperatures contribute to the formation of vacuoles and air bubbles, which decrease powder density (Kelly et al., 2002; Farkye, 2006).

The reconstitution properties (wettability, dispersibility, and solubility) of white cheese powders are shown in Table 4. Although wettability and dispersibility of powders are mainly affected by the structure and surface properties of the powder particles, solubility is mainly affected by powder composition, especially its protein structure (Kim et al., 2002; Thomas et al., 2004; Henning et al., 2006; Gaiani et al., 2006; Kim et al., 2009a; Schuck, 2011). Accordingly, higher particle size and lower free fat content promote wettability and dispersibility. It has been reported that as the particle size increases, atomization pressure decreases (Freudig et al., 1999; Kim et al., 2002; Schuck, 2011). Our experimental data showed that low atomization pressure had positive effects on wettability and dispersibility of white cheese powder. Furthermore, the results revealed that powder samples with low free fat content (especially at

high outlet air temperatures) had improved wettability and dispersibility, in accordance with other studies (Kim et al., 2002; Gaiani et al., 2006). On the other hand, protein structure modifications; for example, polymerization or denaturation due to thermal processes, Maillard reactions, or oxidation, decrease dairy powder solubility (Stapelfeldt et al., 1997; Thomas et al., 2004; Schuck, 2011). The most important factor that affected the solubility index of white cheese powder was outlet air temperature. Increasing outlet air temperatures decrease the solubility index, as reported by other researchers (Anandharamakrishnan et al., 2007, 2008). The relationship between browning index and physical properties of white cheese powders produced at different outlet air temperatures was clear (Tables 3 and 4). The Maillard reaction may be one of the most important factors affecting the physical properties of cheese powder.

There is little evidence on the effects of spray drying on the free fat content of food products (Vignolles et al., 2007; Park et al., 2014); our results are shown in Table 4. The main factor that affected free fat content was outlet air temperature. Increasing outlet air temperatures caused a significant reduction in free fat content

Table 3. Variation in color features of cheese powder with process conditions of spray drying (means $\pm$ SD)

Item ¹	Inlet temperature		
	160°C	195°C	230°C
<i>L</i>	94.67 $\pm$ 0.23 ^a	94.62 $\pm$ 0.34 ^a	94.42 $\pm$ 0.36 ^a
<i>a</i>	-0.27 $\pm$ 0.05 ^a	-0.24 $\pm$ 0.11 ^a	-0.15 $\pm$ 0.06 ^a
<i>b</i>	12.51 $\pm$ 0.77 ^a	12.70 $\pm$ 0.61 ^a	12.68 $\pm$ 0.44 ^a
ΔE : slurry	3.30 $\pm$ 0.22 ^a	3.30 $\pm$ 0.52 ^a	3.85 $\pm$ 0.43 ^a
ΔE : cheese	10.94 $\pm$ 1.93 ^a	10.42 $\pm$ 1.30 ^a	11.31 $\pm$ 1.54 ^a
Chroma	12.51 $\pm$ 0.77 ^a	12.70 $\pm$ 0.61 ^a	12.68 $\pm$ 0.44 ^a
Browning index	13.62 $\pm$ 0.95 ^a	13.89 $\pm$ 0.82 ^a	13.96 $\pm$ 0.56 ^a
Nonenzymatic browning (OD/g of DM)	0.127 $\pm$ 0.002 ^{ab}	0.120 $\pm$ 0.006 ^a	0.133 $\pm$ 0.005 ^b
	Atomization pressure		
	294 kPa	441 kPa	588 kPa
<i>L</i>	94.33 $\pm$ 0.24 ^a	94.62 $\pm$ 0.34 ^a	94.72 $\pm$ 0.52 ^a
<i>a</i>	-0.22 $\pm$ 0.04 ^a	-0.24 $\pm$ 0.11 ^a	-0.13 $\pm$ 0.19 ^a
<i>b</i>	13.11 $\pm$ 0.27 ^b	12.70 $\pm$ 0.61 ^{ab}	12.10 $\pm$ 0.17 ^a
ΔE : slurry	3.28 $\pm$ 0.12 ^a	3.30 $\pm$ 0.52 ^a	3.53 $\pm$ 0.35 ^a
ΔE : cheese	9.45 $\pm$ 0.36 ^a	10.42 $\pm$ 1.30 ^a	10.29 $\pm$ 0.24 ^a
Chroma	13.11 $\pm$ 0.27 ^b	12.70 $\pm$ 0.61 ^{ab}	12.10 $\pm$ 0.61 ^a
Browning index	14.44 $\pm$ 0.26 ^b	13.89 $\pm$ 0.82 ^{ab}	13.25 $\pm$ 0.29 ^a
Nonenzymatic browning (OD/g of DM)	0.176 $\pm$ 0.011 ^c	0.120 $\pm$ 0.006 ^a	0.141 $\pm$ 0.001 ^b
	Outlet temperature		
	60°C	80°C	100°C
<i>L</i>	95.05 $\pm$ 0.47 ^b	94.62 $\pm$ 0.34 ^b	84.32 $\pm$ 0.67 ^a
<i>a</i>	0.09 $\pm$ 0.00 ^b	-0.24 $\pm$ 0.11 ^a	3.93 $\pm$ 0.23 ^c
<i>b</i>	10.22 $\pm$ 0.37 ^a	12.70 $\pm$ 0.61 ^b	19.53 $\pm$ 1.27 ^c
ΔE : slurry	5.66 $\pm$ 0.63 ^b	3.30 $\pm$ 0.52 ^a	9.85 $\pm$ 0.98 ^c
ΔE : cheese	13.27 $\pm$ 1.21 ^c	10.42 $\pm$ 1.30 ^b	2.18 $\pm$ 0.66 ^a
Chroma	10.22 $\pm$ 0.37 ^a	12.70 $\pm$ 0.61 ^b	19.92 $\pm$ 1.26 ^c
Browning index	11.18 $\pm$ 0.48 ^a	13.89 $\pm$ 0.82 ^b	29.28 $\pm$ 2.22 ^c
Nonenzymatic browning (OD/g of DM)	0.142 $\pm$ 0.013 ^a	0.120 $\pm$ 0.006 ^a	0.343 $\pm$ 0.022 ^b

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

¹*L* = lightness; *a* = red-green color; *b* = yellow-blue color; ΔE : slurry = color difference, with white cheese slurry as reference; ΔE : cheese = color difference, with white cheese as reference; browning index was calculated using *L*, *a*, and *b*; OD = optical density.

of white cheese powder. Conflicting experimental results are reported for the effect of inlet air temperature on free fat content (Vignolles et al., 2007). Park et al. (2014) reported that spray drying of whey protein concentrate at an inlet air temperature of 200°C increased the surface free fat content relative to that at 220°C but not 180°C. In contrast, in the current study, an increase in inlet air temperature caused an increase in free fat content. The formation of capillaries and vacuoles, which make fat more susceptible to spray-drying conditions, increases with high inlet air temperatures, resulting in greater free fat content (Farkye, 2006).

Atomization during spray drying had a similar physical effect as homogenization. As the emulsifying degree of fat increases with homogenization, free fat content decreases (Kelly et al., 2002, 2009b; Vignolles et al., 2007). Free fat content is inversely related to particle size, and increasing atomization pressure causes a decline in the particle size (Farkye, 2006). Scanning

electron micrographs of white cheese powders produced at different atomization pressures showed that high atomization pressure resulted in larger numbers of small particles in the powder (Figure 1a, b, and c). Wrinkled particles of different sizes were observed. Particle size is an important factor in surface free fat of dairy powders. A reduction in particle size represents an increase in surface area per unit mass, resulting in more particle surface being covered by free fat (Park and Drake, 2014). In contrast, in this study, high atomization pressure (588 kPa) resulted in lower free fat content than did lower atomization pressures (294 and 441 kPa), which may be related to shape and surface structure. There is a lack of clear information on the effect of outlet air temperature on free fat content. Kim et al. (2009b) reported a positive correlation between free fat content and outlet air temperature. However, those authors did not maintain constant inlet air temperatures when increasing outlet air temperatures. In contrast,

Table 4. Variation of physical properties of white cheese powder with process conditions of spray drying (means $\pm$ SD)

Item	Inlet temperature		
	160°C	195°C	230°C
Bulk density (kg/m ³)	251.0 $\pm$ 6.8 ^b	235.2 $\pm$ 3.6 ^a	238.1 $\pm$ 4.0 ^a
Tapped density (kg/m ³)	473.7 $\pm$ 2.0 ^b	469.8 $\pm$ 5.4 ^b	456.5 $\pm$ 5.6 ^a
Particle density (kg/m ³)	1036.0 $\pm$ 5.2 ^b	1046.3 $\pm$ 22.0 ^b	975.2 $\pm$ 17.3 ^a
Wettability (s)	86.3 $\pm$ 7.8 ^a	121.4 $\pm$ 14.9 ^b	138.8 $\pm$ 26.6 ^b
Dispersibility (%)	75.37 $\pm$ 4.05 ^a	73.13 $\pm$ 2.13 ^a	76.46 $\pm$ 1.24 ^a
Solubility index (%)	72.67 $\pm$ 0.42 ^a	75.95 $\pm$ 1.16 ^b	76.81 $\pm$ 0.96 ^b
Free fat content (%)	39.71 $\pm$ 0.45 ^a	40.89 $\pm$ 0.45 ^b	40.78 $\pm$ 0.99 ^b
Water activity	0.138 $\pm$ 0.021 ^a	0.236 $\pm$ 0.020 ^c	0.179 $\pm$ 0.026 ^b
Item	Atomization pressure		
	294 kPa	441 kPa	588 kPa
Bulk density (kg/m ³)	247.1 $\pm$ 3.6 ^b	235.2 $\pm$ 3.6 ^a	250.9 $\pm$ 5.8 ^b
Tapped density (kg/m ³)	472.9 $\pm$ 5.3 ^a	469.8 $\pm$ 5.4 ^a	495.3 $\pm$ 6.4 ^b
Particle density (kg/m ³)	1044.4 $\pm$ 6.9 ^a	1046.3 $\pm$ 22.0 ^a	1031.7 $\pm$ 5.9 ^a
Wettability (s)	59.2 $\pm$ 17.5 ^a	121.4 $\pm$ 14.9 ^b	83.2 $\pm$ 10.0 ^a
Dispersibility (%)	75.64 $\pm$ 0.68 ^b	73.13 $\pm$ 2.13 ^b	69.55 $\pm$ 0.98 ^a
Solubility index (%)	77.13 $\pm$ 1.72 ^b	75.95 $\pm$ 1.16 ^{ab}	74.88 $\pm$ 0.39 ^a
Free fat content (%)	40.86 $\pm$ 0.79 ^b	40.89 $\pm$ 0.45 ^b	38.84 $\pm$ 0.41 ^a
Water activity	0.124 $\pm$ 0.016 ^a	0.236 $\pm$ 0.020 ^b	0.210 $\pm$ 0.020 ^b
Item	Outlet temperature		
	60°C	80°C	100°C
Bulk density (kg/m ³)	254.2 $\pm$ 11.1 ^c	235.2 $\pm$ 3.6 ^b	216.0 $\pm$ 8.8 ^a
Tapped density (kg/m ³)	489.6 $\pm$ 8.4 ^c	469.8 $\pm$ 5.4 ^b	407.0 $\pm$ 5.6 ^a
Particle density (kg/m ³)	1079.3 $\pm$ 18.5 ^c	1046.3 $\pm$ 22.0 ^b	838.5 $\pm$ 10.7 ^a
Wettability (s)	160.3 $\pm$ 25.7 ^c	121.4 $\pm$ 14.9 ^b	18.9 $\pm$ 1.9 ^a
Dispersibility (%)	65.23 $\pm$ 0.83 ^a	73.13 $\pm$ 2.13 ^b	86.54 $\pm$ 0.39 ^c
Solubility index (%)	78.03 $\pm$ 0.62 ^b	75.95 $\pm$ 1.16 ^b	54.45 $\pm$ 3.43 ^a
Free fat content (%)	41.65 $\pm$ 0.49 ^b	40.89 $\pm$ 0.45 ^b	35.16 $\pm$ 0.16 ^a
Water activity	0.244 $\pm$ 0.036 ^b	0.236 $\pm$ 0.020 ^b	0.135 $\pm$ 0.021 ^a

^{a-c}Means within a row with different superscripts differ ($P < 0.05$).

Keogh et al. (2004) reported a reduction in free fat at outlet air temperatures up to 100°C; however, they did not report the formation or variation of free fat because their study was focused on particle size. In this study, a negative correlation was found between free fat content and outlet air temperature (Table 4).

Water activity values measured in white cheese powder samples fluctuated with spray-drying conditions (Table 4). However, all water activity values obtained were <0.300 , indicating that the powder samples were safe with respect to microbiological growth and chemical reactivity (Roos, 2007; Tapia et al., 2007).

Sensory Evaluation

The sensory evaluation results are shown in Figure 2. The sensory properties of white cheese powder produced with different inlet air temperatures and atomization pressures were not significant (Figure 2a and 2b); however, outlet air temperature contributed to significant effects on sensory properties (Figure 2c).

Panelists reported increased browning, sensorial caking, and scorched flavor at outlet air temperature of 100°C. We found no significant differences in cheese flavor with outlet temperatures between 60°C and 80°C (sensorial scores of 6.53 ± 0.15 and 6.99 ± 0.25 , respectively); however, an outlet air temperature of 100°C contributed to lower cheese flavor scores (5.38 ± 0.45).

CONCLUSIONS

White cheese powders were produced under different spray-drying conditions, and the effects of spray-drying conditions (inlet air temperature, atomization pressure, and outlet air temperature) on powder quality properties were evaluated. The most important process parameter was outlet air temperature: white cheese powders produced at high outlet air temperatures had increased browning. All white cheese powder samples had a moisture content $<2.85\%$ and a water activity value of 0.300; therefore, they were safe with respect to

Figure 1. Scanning electron micrographs of cheese powders produced at different atomization pressures: (a) 294 kPa, (b) 441 kPa, and (c) 558 kPa.

microbiological growth and chemical reactivity. White cheese powder samples with low free fat content had enhanced wettability and dispersibility. Solubility index improved with decreasing temperature. Free fat content was negatively correlated with outlet air temperature and atomization pressure, and positively correlated

with inlet air temperature. All white cheese powder samples produced in this study had acceptable sensorial properties except for those produced at an outlet air temperature of 100°C; these samples had higher scorched flavor and color scores and lower cheese flavor scores.

Figure 2. The effects of variation of spray-drying process conditions: (a) inlet air temperature, (b) atomization pressure, and (c) outlet air temperature, on sensory properties of white cheese powder. Color version available online.

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