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Physical characteristics of spray-dried dairy powders containing different vegetable oils

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ABSTRACT

The objective of this study was to investigate the physical characteristics of spray-dried dairy powders formulated with different oil types, spray-dried at different outlet temperatures. A model fat-filled dairy formulation (target 40% w/w total solids, comprising protein, oil and lactose) containing lactose (23.9%), sodium caseinate (5.11%) and sunflower (SO) or palm (PO) oil or a 50:50 mixture of SO/PO (in all cases 11.5% total oil) were heat-treated, homogenised and spray-dried at an outlet temperature of 80 or 90 °C. Increasing outlet temperature reduced water content, water activity and tapped bulk density, irrespective of oil type, and increased solvent-extractable free fat for all oil types. Onset of glass transition (T_g) and crystallisation (T_{cr}) decreased at the lower outlet temperature. Oil type had no effect on powder moisture, water activity (a_w), powder bulk density, particle size, fat globule size of emulsion or fat globule size of reconstituted fat-filled dairy powders.

1. Introduction

The shelf-life of dairy products can be increased by transforming them into a dry product by spray-drying. In a powder form, storage, handling and transport are also easier. The oil component in dairy powders influences flowability and rehydration (Fäldt, 1995). Oils of non-dairy origin, from a wide range of sources, are frequently utilised in the formulation of dairy-based powders, such as infant formulae, to achieve fatty acid profiles. In the manufacturing process, proteins act as surfactants to produce stable oil-in-water emulsions, stabilising the system to separation/creaming, protecting the fat from oxidation and reducing powder handling problems (Matsuno and Shuji, 1993).

Various forms of casein and whey proteins (WP) are used as emulsifiers in dairy-based formulations and powders. Non-micellar casein as found in sodium caseinate (NaCas) may be considered a flexible protein that can readily unfold to form an interfacial layer. Micellar casein behaves differently to non-micellar casein, as calcium bridges restrict the extent to which casein micelles unfold and adsorb at the interface. NaCas depresses interfacial tension more effectively than whey proteins, as it diffuses more quickly to an interface and, on reaching the interface, absorbs more quickly than the other proteins (Phillips and Williams, 2000). WP denaturation occurs during concentration, evaporation and drying, which leads to a less stable emulsion and increased surface fat and larger droplets after reconstitution, whereas NaCas-stabilised emulsions are considerably more heat-stable (Vega and Roos, 2006).

Free fat, i.e. fat that is no longer emulsified, is located at the powder particle surface and in pores and capillaries created during the drying process. In spray-dried powders free fat is of concern because it has a tendency to oxidise, and the reconstituted product loses its organoleptic appeal due to the formation of free fat pools on the surface of the liquid. Free fat in dairy powders is influenced by product composition, homogenisation pressure, spray-drying inlet/outlet temperatures and storage conditions of powders (Vignolles et al., 2007).

Other studies have examined the effect of spray-drying temperature on the surface fat of dairy powders but have varied both inlet and outlet temperatures simultaneously rather than independently (Gaiani et al., 2010; Kim et al., 2009). Prolonged storage of dairy powders at a high relative humidity (RH) can lead to lactose crystallisation which reduces the integrity of the protein-based interfacial layer and results in increased free fat levels (McCarthy et al., 2013). One study found that the use of a fat in its native state compared to a blend of native and hardened fats reduced free fat level in a NaCas-stabilised fat-filled emulsion containing lactose (Millqvist-Fureby, 2003).

Confocal laser scanning microscopy (CLSM) has been used to visualise fat distribution on particles of whole milk powder (WMP) and spray-dried cream powder (Auty et al., 2001; Vignolles et al., 2010). In the last 15 years, X-ray photoelectron spectroscopy (XPS) has been applied to investigate the surface composition of

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dairy powders. From carbon, oxygen and nitrogen percentages, surface composition can be calculated by empirical calculations. During spray-drying, rapid evaporation of water occurs, which leads to the migration of milk components to or from the surface of the drying droplet, due to concentration gradients. Studies using XPS have shown that fat can be overly-represented on the surface of powders compared to bulk phase composition, e.g., powder surface being composed of 98% fat of WMP compared to 29% in the bulk (Kim et al., 2003). Fat type influences the level of surface fat, with fats having intermediate melting points showing the highest surface fat values, while increased homogenisation pressure creates smaller fat globules, resulting in less free fat (Millqvist-Fureby, 2003). During spray-drying, rapid evaporation of water occurs, which leads to the migration of milk components to or from the surface of the drying droplet, due to concentration gradients.

The aim of this study was to investigate the physical characteristics of a spray-dried dairy powder made with different blends of vegetable oils, namely palm oil, sunflower oil or a 50:50 blend of the two oils, in order to determine if oil type affects physical properties in a model dairy-based emulsion, produced at two different spray-dryer outlet temperatures while keeping inlet temperature constant.

2. Materials and methods

2.1. Materials

Sunflower oil and palm oil were purchased from Trilby Trading (Drogheda, Ireland). Sodium caseinate was purchased from Kerry Ingredients (Listowel, Co. Kerry Ireland) with a protein content of 89.8% and lactose from Glanbia Ingredients (Ballyraggett, Co. Kilkenny, Ireland). Petroleum ether (40–60 °C boiling point) of analytical grade, Nile Red, Fast green and PEG 400 were obtained from Sigma–Aldrich (Wicklow, Ireland).

2.2. Experimental design

The experimental design consisted of six unique trials (Table 1) carried out in triplicate, where the trials for each replicate were carried out in random order. The emulsion consisted of 5.1% NaCas, 11.5% fat, and 23.9% lactose. The experimental design included 3 compositional variations, where the oil fraction was made up of sunflower (SO) and palm (PO) at different ratios as presented in Table 1.

2.3. Preparation of model emulsions

Emulsions (15 kg batch size) were prepared as follows. Lactose powder was dissolved in hot water (~65 °C), using a Silverson L4RT (Silverson Machines Ltd., Waterside, Chesham, Bucks, England) mixer to aid reconstitution. Some fat (~10% of total fat) was added during mixing to reduce foaming. Sodium caseinate (NaCas) was then added slowly before addition of the remaining fat component. When palm oil was used, it was melted in a separate vessel before addition. The mix was tempered to 60 °C and adjusted to pH 6.8 by adding 1 M KOH and kept under high shear for 120 min to ensure complete hydration of the NaCas. The feed was agitated prior to high-temperature short-time heat treatment (100 °C × 30 s) using a Microthermics (Model 25HV; North Carolina, USA) tubular heat exchanger. The mix was homogenised using an in-line 2-stage homogeniser (Model NS20006H, GEA Niro, Soavi, Parma, Italy) using a first-stage pressure of 13.8 MPa and a second-stage pressure of 3.45 MPa, and spray-dried in a pilot-scale Anhydro Spray dryer (Model Plant No. 3 type I KA, Copenhagen, Denmark), equipped with a two-fluid nozzle atomization system (Type 1/8 JAC 316ss) and counter-current drying, with a typical water evaporation rate of 20 L/h. Dryer inlet temperature was held constant at 185 °C and outlet temperature was either 80 or 90 °C to vary the moisture level in the powder. Samples of the emulsion were taken post-heat treatment and post-homogenisation for physico-chemical measurements. Samples of powder were stored at 10 °C in sealed foil bags until analyses were carried out.

Table 1
Experimental design for formulation and spray drying conditions.

Code[a]	Fat type or blend[b]	Outlet temperature (°C)[c]
SO-L	SO	80
SO-H	SO	90
SOPO-L	SOPO	80
SOPO-H	SOPO	90
PO-L	PO	80
PO-H	PO	90

[a] Suffix L and H correspond to lower (80 °C) and higher (90 °C) outlet temperatures, respectively.
[b] SO-Sunflower oil, SOPO-Sunflower oil: Palm oil at 50:50 and PO-Palm oil.
[c] Spray dryer inlet temperature was 185 °C in all cases.

2.4. Measurement of fat globule size and powder particle size

Mean fat globule size of emulsions was determined post-homogenisation and in reconstituted emulsions by laser light scattering with a MasterSizer S laser diffraction instrument (Malvern Instruments Ltd., Worcestershire, UK) equipped with a 300 RF lens. Distilled water was used as the dispersing medium and refractive index values of 1.46 and 1.33 were used for particles and dispersant, respectively (Grompone, 2011). Mean powder particle size analysis was carried out by laser diffraction using the dry-feeding unit for the MasterSizer S, with a pressure setting of 1 bar.

2.5. Rheological measurements

Viscosity was measured at 55 °C using an AR-G2 controlled stress rheometer (TA Instruments, UK) equipped with concentric cylinder geometry in shear rate mode. Samples were pre-sheared at 500 s^{-1} for 1 min, followed by equilibration for 2 min. An upward shear rate sweep was then applied from 5 to 500 s^{-1} over 3 min, followed by holding at 500 s^{-1} for 1 min. The average apparent viscosity measured at 500 s^{-1} was used for comparison of the model formulations. Rheological behaviour was modelled using the power law equation, (Eq. (1)) with a logarithmic transformation and fitted using least squares regression in Microsoft Excel.

$$\log \sigma = \log K + n \log \dot{\gamma} \quad (1)$$

where σ is the shear stress (Pa), K is the consistency index (Pa s^n), $\dot{\gamma}$ is the shear rate (s^{-1}) and n is the flow index, with $n < 1$ for a shear-thinning fluid and $n = 1$ for a Newtonian fluid.

2.6. Determination of physico-chemical properties

Sample pH was monitored using a pH 330i meter (WTW, Weilheim, Germany). The powder water content was determined using a halogen rapid moisture analyser (HR-83 Halogen, Mettler Toledo, Switzerland). The samples were dried at a temperature of 105 °C until a constant weight was attained (<1 mg change over 140 s, equivalent to ±0.025%). Water activity (a_w) was measured with a Novasina LabMaster-a_w water activity meter (Novatron Scientific Ltd., West Sussex, UK). Powder bulk density was determined according to the IDF Standard 134A:1995.