Investigation of the flowability, thermal stability and emulsification properties of two milk protein concentrates having different levels of native whey proteins

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ABSTRACT

Milk protein concentrate-85 (MPC85) is a dairy ingredient which has a diverse range of applications in food products. The technofunctional properties of two MPC85 samples having similar gross composition but different levels of native whey protein (WP), i.e., MPC85S1 and MPC85S2 with 16.6 and 6.0 g native WP/100 g protein, respectively, were compared. Rheometeric analysis showed that under an applied normal stress of 1.0 – 15.0 kPa, the compressibility, the air permeability and the cohesiveness of MPC85S2 was higher compared to MPC85S1. Differential scanning calorimetry showed that protein denaturation in MPC85S1 began at 63 °C while for MPC85S2 it began at 70 °C. The heat coagulation time (HCT at 140 °C) for 4.2% (w/v, on a protein basis) reconstituted MPC85S1 and MPC85S2 was 2.2 and 2.7 min, respectively. While a higher lightness for MPC85S1 was evidenced using colourimeter analysis, the colour stability on oven drying at 95 °C for MPC85S2 was higher than MPC85S1. The emulsion produced with MPC85S1 flocculated after 1 d and phase separation occurred after 14 d. In the case of MPC85S2, flocculation began after 4 d while phase separation was observed at 33 d. The viscosity of MPC85S2 (4.2% (w/v) protein) was higher than MPC85S1. This study showed differences between the flowability, viscosity, colour properties, thermal stability (in powder and in reconstituted format), emulsification and buffering capacity for MPC samples having two different levels of WP denaturation. The results demonstrated that the MPCs studied having two different levels of WP denaturation could be targeted for different functional applications. The minimal/maximum level of denaturation required to induce technofunctional property differences requires further study.

1. Introduction

The global demand for dietary protein has led to the manufacture of new protein-enriched food ingredients. Dairy ingredients are extensively employed for the development of high quality protein fortified food products. The market for high protein content dairy ingredients has previously been dominated by casein and whey protein (WP) products while more recently the utilisation of high protein content milk protein concentrates (MPC), such as MPC80 and MPC85, has significantly increased (Meena, Singh, & Panjagari, 2017a). High protein MPCs can be incorporated into food products to confer specific characteristics such as improved technofunctional and nutritional properties. Therefore, high protein content MPCs have been widely employed in the formulation of nutritional beverages, infant formula, yoghurts and cheeses, etc (Agarwal, Beausire, Patel, & Patel, 2015).

One of the challenges for the widespread utilisation of MPC in different food applications is associated with variability in its technofunctional properties (Khalesi & FitzGerald, 2021). The factors which may lead to this variation include differences in gross composition as a result, e.g., of seasonal variation and different milk sources along with differences in the manufacturing conditions. The latter may change the interactions between proteins and between proteins and other molecules (e.g., lactose, calcium, lipid, water), and may lead to protein cross-linking and denaturation (Bulca, Dumpler, & Kulozik, 2016; Warncke & Kulozik, 2020). The proteins in MPC consist ~ 20% WP, which is similar to bovine milk. However, part of the WP may be denatured during the processing of milk, this depends on the conditions employed during specific stages, e.g., the duration and temperature used during pasteurisation and spray drying. The impact of WP denaturation on the technofunctional properties of MPC does not appear to have been

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extensively investigated.

Powder compressibility, air permeability and aerated energy are important indexes used to characterise MPC powder flowability properties. Highly flowable MPCs are less likely to lead to equipment blockage during handling (Crowley, Gazi, Kelly, Huppertz, & O'Mahony, 2014a). The flowability of dairy powders is a surface dependent property. Powder particles with smaller sizes and larger surface areas have been reported to be more prone to the development of cohesiveness (Zafar, Vivacqua, Calvert, Ghadiri, & Cleaver, 2017). The contribution of partial denaturation of WP in whey protein concentrate (WPC) on powder flow behavior has been reported to be complex and is mostly attributed to morphological differences in the structure of aggregated protein particles in denatured WPC (Zhang, Arrighi, Campbell, Lonchamp, & Euston, 2016). These authors reported that denaturation in WPC led to a higher extent of inter-particle interactions thereby resulting in a higher resistance to flow. Denaturation of WP during spray drying of dairy powders has been reported to lead to the accumulation of water interfacial properties (DSC), turbidity assessment and more routinely by measuring rheometry (DSC), turbidity assessment and more routinely by measuring

2. Materials and methods

2.1. Reagents

Hydrochloric acid (HCl) was from VWR (Dublin, Ireland). Sodium hydroxide (NaOH) and acetic acid were from Fisher Scientific (Dublin, Ireland). Boric acid, Kjeldahl catalyst tablets (free of Hg and Se), sulphuric acid ≥ 98% and other reagents were from Sigma chemical company (Dublin, Ireland). All other reagents were of analytical grade. Sunflower oil was purchased from a local market.

2.2. Properties of MPCs

The MPC85 (MPC85S1 and MPC85S2) powders were provided by a commercial supplier. The moisture content of MPC85S1 and MPC85S2 was determined according to IDF/ISO (2004). The lipid content was determined using the AOAC (2000) method. Ash was determined using the method outlined by Connolly, Piggott, and FitzGerald (2013). Protein content was determined according to FIL-IDF standard 208 (1993). Lactose was calculated by difference. The level of native WP/total protein (%) was determined according to the methodology of Sutariya, Dhand, and Joyce, Kelly, and O’Mahony (2018) by the determination of the pH of 4.6-soluble protein fraction. The moisture, lipid, lactose, ash and protein content in MPC85S1 were 4.82, 1.47, 2.52, 7.02 and 84.17 g/100 g powder, respectively, while for MPC85S2 these values were 4.70, 1.31, 1.41, 7.00 and 85.58 g/100 g powder, respectively. The native WP in MPC85S1 and MPC85S2 was 16.62 ± 0.23 and 6.03 ± 0.20 g/100 g protein, respectively. The raw milk used to manufacture the MPCs herein was similar and the final MPC powders had a similar storage history.

2.3. Powder properties

2.3.1. Flowability of MPC

An FT4 powder rheometer (Freeman Technology, Tewkesbury, UK) was used for characterisation of powder flowability. The FT4 powder rheometer measures the dynamic flow, shear and bulk properties of powders. This device consists of a glass container and a rotating blade which moves across the sample bed. The standard FT4 blade is rotated and moved downwards through the powder at a specific blade tip speed. A conditioning step was applied by splintering the powder in a split vessel (25 mm x 10 mL) with a FT4 blade (23.5 mm) which was moved up and down by a piston through the powder bed at a speed of 60 mm s⁻¹. This aimed to provide uniformly packed powder particles (Freeman, 2007). The specific flow properties of the MPC powders including compressibility, air permeability and powder aerated energy were measured as follows:

- MPC is used as an emulsifier in a range of food products, e.g., in whipped toppings, coffee creamers, soups, etc. It has been reported that partial denaturation of WP in MPC85 results in the exposure of reactive or charged groups (normally buried within the interior of native protein molecules) which may have a positive impact on the emulsification properties (Manoj & Rizvi, 2009; Gopirajah, Singh, Javad, & Rizvi, 2020). However, the level of WP denaturation in MPC required to provide this beneficial effect does not appear to have been reported in the literature.

- Previously, Holt et al. (1999a and b) reported differences in the functional properties (e.g., surface tension, thermal stability and oil/water interfacial properties) of commercial and semi-commercial WP products as being associated with the level of WP denaturation. Liu et al. (2021) also suggested that the ratio of casein/WP is an important factor governing the denaturation mechanism of dairy protein ingredients. In addition, the interaction of the denatured WP with caseins has been shown to change the physical properties (e.g., viscosity and colour) of concentrated milk (Dumpler et al., 2020). While the effect of MPC composition on different technofunctional properties has been extensively studied, the impact of the level of protein denaturation on different technofunctional properties of MPCs appears to have been less studied.

The hypothesis is that the presence of WP at different levels of denaturation should differentially impact the functional properties of MPCs due to the heat induced formation of casein-WP aggregates, which in turn should alter the flowability, apparent viscosity, thermal stability, emulsification and other technofunctional properties of the resulting MPCs. Therefore, the objective of this study was to investigate the impact of the level of WP denaturation on some important technofunctional properties of MPCs.

Compliance with ethical standards

All applicable institutional and/or national guidelines for the care and use of animals were followed. All animal studies were approved by the relevant Ethical Committee. All procedures were performed in accordance with the ARRIVE guidelines.
2.3.1.1. Compressibility measurement. An FT4 powder rheometer equipped with a vented piston for compression of the samples under normal stress was used for measurement of the compressibility of MPC85S1 and MPC85S2 (n = 3). The powder sample was preconditioned as described above. After that, different pressures (1, 2, 4, 6, 8, 10, 12 and 15 kPa) were applied using an FT4 blade (23.5 mm) to the bulk powder. Each pressure was applied until the powder reached its stress equilibrium, i.e., where the powder was at its equilibrium stress where there was no net force (stress) on the powder. The distance travelled by the piston was measured for each applied stress and the percentage change in volume after each compression (compressibility (%)) was calculated.

2.3.1.2. Air permeability analysis. The air permeability of MPC85S1 and MPC85S2 was also analysed using an FT4 powder rheometer (n = 3). The powder was first prepared by conditioning as outlined earlier. A container vessel (25 mm × 10 mL) and a blade (23.5 mm) were used. Pressure (1 to 15 kPa) was applied until reaching stress equilibrium. The air pressure drop across the powder bed (mbar) was recorded for each air velocity n.

2.3.1.3. Powder aerated energy. Powder aerated energy was also determined using an FT4 powder rheometer (n = 3). During measurement of the aerated energy of MPC85S1 and MPC85S2, air was introduced at different air velocities (0, 2, 4, 6, 8 and 10 mm/s) to a vessel (25 mm × 25 mL) containing the MPC powder samples. The energy (mJ) required for an FT4 blade (23.5 mm) to stir the powder was then measured. The aerated energy and aeration ratio were calculated using Eqs. (1) and (2):

\[
\text{Aerated Energy (mJ) = Energy at air velocity n} \tag{1}
\]

\[
\text{Aeration ratio} = \frac{\text{Energy at air velocity 0}}{\text{Energy at air velocity n}} \tag{2}
\]

where the aerated energy, at air velocity 0, is defined as the energy required to stir the powder sample without aeration while the aerated energy n refers to the aerated energy required to stir the powder sample subjected to the air velocity n.

2.3.2. Measurement of powder colour

The colour of the MPC powder samples was measured (n = 5) using a colourimeter (Spectrophotometer CR-600d, Konica Minolta Inc., Japan). The samples were also dried at 95 °C in a vacuum oven (Gallenkamp, Gallenkamp Ltd, Loughborough, UK) for 6 h to remove residual moisture and the powders were subsequently subjected to colour analysis. The results were expressed according to the CIELAB model where L* represents lightness, a* represents the redness and b* indicates the yellowness. The overall colour differences (ΔE) of each sample before and after drying was calculated according to Eq. (3):

\[
\Delta E = \sqrt{(L_i - L_0)^2 + (a_i - a_0)^2 + (b_i - b_0)^2} \tag{3}
\]

where \(L_i\) (lightness indicator), \(a_i\) (redness indicator) and \(b_i\) (yellowness indicator) are the colour indicators for the dried MPC samples and \(L_0\), \(a_0\) and \(b_0\) are the colour indicators of the MPC samples before drying.

2.3.3. Thermal behavior of MPC powder

2.3.3.1. Thermogravimetric analysis. Thermogravimetric analysis (TGA) of MPC85S1 and MPC85S2 was carried out using a TGA 4000 System (Perkin Elmer, Waltham, USA) (n = 2). Samples (4–6 mg) of MPC85S1 and MPC85S2 were exposed to a temperature ranging from 30 to 400 °C at a heating ramp of 10 °C min⁻¹. Nitrogen was used as a carrier gas at a constant flow rate of 100 mL min⁻¹ during the analysis. The weight loss during heating was recorded.

2.3.3.2. Differential scanning calorimetry (DSC). DSC was performed using a Polyma 214 DSC (NETZSCH-Geratebau GmbH, Germany) (n = 2). Samples (4–6 mg) of MPC85S1 and MPC85S2 were sealed in Al pans and were then heated from 25 to 95 °C (first heating stage) in order to follow protein denaturation. The samples were then cooled to 25 °C (cooling stage) in order to investigate the thermal behaviour of the MPC samples during cooling. Lastly, the samples were heated from 25 to 400 °C (second heating stage) in order to investigate the physical behaviour and possible aggregation of WP-caseins in MPCs during heating at higher temperatures (>95 °C). The rate of heating/cooling during the scans was set at 10 °C min⁻¹. An empty Al pan was used as a reference. Experiments were carried out under an atmosphere of nitrogen. The difference in heat flow between the sample and the reference was recorded.

2.4. Technofunctional properties of reconstituted MPC

2.4.1. Heat coagulation time and heat induced gelling time of reconstituted MPC

The heat coagulation time (HCT) and the heat induced gelling time (HIT) of the MPC85S1 and MPC85S2 samples at a protein concentration of 4.2% (w/v) were determined after adjustment to pH 7.0 (n = 5). In order to ensure maximal hydration, the samples were initially dissolved at room temperature for 1 h and were then maintained at 4 °C for 24 h. Aliquots (2.3 mL) of the samples were transferred into glass tubes (length = 130 mm; external diameter = 10 mm; thickness = 2 mm) and sealed with rubber stoppers. The tubes were then placed in a metal rack and immersed in an oil bath (Elbanton BV, Kerkdriel, The Netherlands) set at 110, 120, 130 and 140 °C with constant slow oscillation (8 swings/ min). The HCT was considered as the time from putting the samples in the oil bath to the first visible onset of coagulation (clots). The HIT (at 140 °C) was considered as the time elapsed between putting the sample in the oil bath and the time when gelation appeared and liquid flow stopped.

2.4.2. Apparent viscosity measurement of reconstituted MPC

The apparent viscosity of rehydrated suspensions of MPC85S1 and MPC85S2 at two protein concentrations (1.7% and 4.2% (w/v)) was determined at 30 °C using a DV-II viscometer (Brookfield, Harlow, UK). Rehydrated suspensions (16 mL) were transferred to the low volume sample container of the viscometer. An LV-1 spindle (Brookfield) was used to generate a shear rate of 100 s⁻¹. The mean viscosity (mPa.s) was reported (n = 5).

2.4.3. Emulsification properties of MPC

Reconstituted MPC samples (4.2% w/v, protein) were prepared by dissolving 5.0 g sample in 100 mL dH₂O at 50 °C for 30 min. Samples were adjusted to pH 7.0 (using 1 M HCl/NaOH where required) and were gently stirred for 30 min to complete dissolution. Sunflower oil containing sodium azide at 0.02% (w/v), as an antimicrobial agent, was used as the oil phase. A blend of protein suspension:sunflower oil (3:1, v/v) was mixed using an Ultra-Turrax (IKA T25, Staufen, Germany) homogenizer at 16000 rpm for 1 min (Conolly, Piggott, & FitzGerald, 2014). Immediately after the emulsion was generated, it was stabilized by diluting 1:40 in 0.1% (w/v) SDS. The mean particle size of the emulsions was measured using a Mastersizer 2000 (Malvern, Worcestershire, UK) equipped with an Hydro 2000HS sample dispersion system (set at a stirring speed of 1000 rpm) interfaced with Mastersizer 2000 software (version 5.61; Malvern Instruments, Malvern, UK). The analysis was performed on day 1, 4, 14 and 33 (samples were stored quiescently at 4 °C). The particle refractive index and the continuous phase refractive index were 1.52 and 1.33, respectively. The beam length was 2.35 mm and the minimum detection limit was 0.02 μm. Measurement integration time was 12000 ms (n = 3).
2.4.4. Ethanol stability and acid-buffering capacity

The ethanol stability was determined after adjusting the pH of 4.2% (w/v, on a protein basis) MPC85 aqueous suspensions to pH 7.0 at 21 °C. The samples were then mixed with ethanol at different concentrations (30.0, 40.0, 50.0, 60.0, 70.0, 80.0, 90 and 99.9% (v/v)) at a volume ratio of 1:0.2:4 (protein suspension sample:ethanol solution) and the mixture was vortexed for 30 s. The ethanol stability was considered as the lowest concentration of aqueous ethanol solution required to induce protein flocculation (Lin, Kelly, O’Mahony, & Guinee, 2018).

Acid-buffering capacity of MPC samples was estimated (n = 3) at room temperature using the method described by Al-Dabbas, Al-Ismail, and Al-Abdullah (2011). The samples were adjusted to pH 7.0 using 0.1 N HCl or NaOH where required and were then titrated to pH 4.0 using 0.1 N HCl using 25 mL of 4.2% (w/v, protein basis) reconstituted MPC. Buffering index values (ΔpH/ΔmH) were calculated according to Eq. (4) (Raouche, Dobenesque, Bot, Lagaude, & Marchesseau, 2009):

\[ \frac{\Delta pH}{\Delta mH} = \frac{\text{volume of acid} \times \text{normality}}{\text{volume of reconstituted MPC} \times \Delta pH} \]  

(4)

where ΔpH represents the change in pH (which was 3.0 units in this experiment).

2.5. Statistical analysis

Data values were presented as mean ± standard deviation (SD). Statistical analysis was carried out by means of ANOVA tests using Minitab® Release 15 for Windows. A p value < 0.05 was considered as statistically significant.

3. Results and discussion

3.1. Powder properties

3.1.1. Flowability of MPC

Powder flowability refers to the ability of a powder to flow as individual particles and is directly influenced by powder cohesion which refers to a tendency of particles to interact via a combination of hydrophobic and electrostatic interactions, hydrogen bonding and Van der Waals forces (Nan, Ghadiri, & Wang, 2017).

Compressibility: The compressibility of MPC85S2 with an applied pressure of between 1 and 15 kPa was higher than that of MPC85S1, e.g., the compressibility (%) at an applied normal stress at 8 kPa for MPC85S1 and MPC85S2 was 25.48 and 28.88%, respectively (Fig. 1a). However, the difference between the compressibility of MPC85S2 and MPC85S1 was reduced from ~11.5 to 7.4% by increasing the applied pressure between 1 and 15 kPa. It would appear that there was more interstitial air in MPC85S2 when compared with MPC85S1 which may have resulted in its higher compressibility. The difference between the compressibility of MPC85S1 and MPC85S2 may be associated with differences in their inter-particle interactions and particle morphology (i.e., generation of agglomerated and non-spherical particles due to denaturation) as a result of differences in the level of native WP. In a study by Fournaise et al. (2020) the compressibility of dairy powders including skim milk powder (SMP, 16.13 ± 0.91%), semi-skim milk powder (SSMP, 42.50 ± 3.54%) and whole milk powder (WMP, 39.44 ± 3.67%) were determined at an applied pressure of 15 kPa using an FT4 powder rheometer. The authors concluded that the lower compressibility of SMP compared to the other samples was related to its lower lipid content, i.e., 1.5% for SMP vs 13.8 and 26.0%, respectively, for SSMP and WMP. The percentage compressibility values of the MPCs studied herein at a similar applied pressure, i.e., 15 kPa (28.41 ± 0.91% for MPC85S1 and 30.07 ± 0.47% for MPC85S2) were lower than those reported for SSMP and WMP (with higher fat content) while they were higher than that for SMP with similar lipid content (~1.5%). The higher compressibility values of the MPCs studied herein compared to those previously reported for SMP may be related with other composition (and processing) differences between the samples as, e.g., the protein, lactose and ash contents of the SMP were 32.9, 56.0 and 8.5%, respectively. Previous studies reported the compressibility of MPC70-90 to be between ~5 to ~25% when applying pressures between 0.5 and 15 kPa (Babu et al., 2018). The compressibility of MPC70, when applying a pressure of ~14 kPa, was reported to be 26.3 ± 0.5% (Silva & O’Mahony, 2017). High compressibility of MPCs were reported by Crowley et al., (2014a), who suggested that MPCs are susceptible to their own compression during storage in a hopper. The more compressible a powder is, the less flowable it is expected to be due to the presence of larger voids in the powder bed (Tuohy, 1989). However, the link between WP denaturation and compressibility of MPCs does not appear to have been previously reported in the literature.

Air permeability: The air induced pressure drop across the powder bed was also determined for the MPC samples. The powder with a lower pressure drop has higher air permeability. The pressure drop increased in both samples with increasing applied normal stress showing that the
population of large pores in the powder bed was reduced. The pressure drop across the powder bed for MPC85S1, at all applied normal stresses (1–15 kPa), was higher than that for MPC85S2 (Fig. 1b). The air induced pressure drop across the powder bed for MPC85S1 and MPC85S2 for pressures between 1 and 15 kPa was in the range of 1.0–2.5 and 0.5–2.0 mBar, respectively. The difference between the pressure drop across the powder bed of MPC85S1 and MPC85S2 reduced from 40.0 to 17.5% on increasing the pressure from 1 to 15 kPa. The air induced pressure drop across the powder bed for MPC with 88% protein, 1.1% fat, 0.5% lactose, 6.3% ash and 4.6% moisture has been reported to occur between 2 and 3 mBar when applying normal stresses, from 0.5 to 15 kPa, with an air velocity of 2.0 mm/s (Babu et al., 2018). Differences between the composition profiles and the air velocity may account for the variations between the values of the samples herein and those previously reported by Babu et al. (2018).

The higher air permeability of MPC85S2 may be due to a higher agglomeration as a result of higher WP denaturation. A recent study indicated that dairy powder beds having mainly agglomerates had larger permeability compared to non-agglomerated powders (Börjesson, Ingning, Trägårdh, Bergenståhl, & Paulsson, 2016). A higher pressure drop across a powder has been linked with a direct relationship with a higher resistance to powder wetting (Börjesson et al., 2016), i.e., powders with higher permeability are wetted more quickly. These results suggest that MPC85S2 may have a higher wettability compared to MPC85S1, however, this requires further analysis.

**Aerated energy:** The aerated energy was also determined for MPC85S1 and MPC85S2. The aerated energy represents the energy required to displace the powder bed at a certain air velocity. A lower aerated energy indicates a lower tendency for cohesion due to a lower extent of interaction between the particles. The aerated energy was higher for MPC85S1 than for MPC85S2 at an air velocity < 6 mm/s (Fig. 1c). However, at 6 mm/s, the aerated energies were similar (~16 mJ) and at an air velocity > 6 mm/s, the aerated energy of MPC85S2 was higher than MPC85S1.

An aeration ratio at each air velocity was also calculated in order to obtain a better comparison of the cohesive behaviour of the powder particles. By increasing the air velocity, the aerated energy is reduced, thus according to Equation (2), the aeration ratio is > 1. This means that aerated energies obtained in the presence of air flow are only a fraction of the control without air flow.

The aeration ratio for MPC85S1 at different air velocities ranged between 1 and 12, while the ratio for MPC85S2 was in a range of 1.0–3.5. In general, very cohesive powders (or those containing a high level of binders) have aeration ratios between 1 and 2, semi-cohesive powders (most food powders) have aeration ratios between 2 and 20 while powders with low cohesiveness have aeration ratios over 20. Consequently, a higher range of aeration ratios for MPC85S1 compared to MPC85S2 is indicative of a lower cohesiveness in this powder. The aerated energies of WP and demineralised WP were reported to be 4.8 and 10.1 mJ, respectively, when tested at an air velocity of 4 mm/s (Lapézik et al., 2014). The aerated energy for MPC85S1 and MPC85S2 at air velocity of 4 mm/s was equal to 22.4 and 18.7 mJ, respectively, showing higher cohesiveness of MPCs herein compared to the WP products tested by Lapézik et al. (2014). This may be due to the higher extent of cross-linkages between the casein molecules and between casein-WPs in MPCs, compared to the WPs. These results would concur with the findings in the present study where the higher level of WP denaturation in MPC85S2 may have resulted in increased interaction between caseins-WPs, thus increased the cohesiveness which was indicated by a lower aeration energy in MPC85S2. This appears to be the first report on the aerated energy of MPC.

MPC composition and processing conditions influence flowability (Kim, Xiao, & Pearce, 2005). As MPC85S1 and MPC85S2 had similar gross composition profiles, the difference in the flowability parameters (such as compressibility, permeability and aerated energy) of the MPCs herein should be related to differences in the level of agglomeration and WP denaturation. Overall, MPC85S2 with a lower native WP content had a higher compressibility, higher air permeability and a lower aerated ratio compared to MPC85S1.

### 3.1.2. Colour measurement

Colour is an important parameter in the consumer perception of food products. The colour of MPC85S1 and MPC85S2 was compared in the case of powder lightness (L*), redness (a*) and yellowness (b*). The results showed that MPC85S1 had a higher L* value. The lower lightness of MPC85S2 may be due to a higher extent of Maillard reaction product formation (Le; Bhandari, & Deeth, 2011). Furthermore, the L* value of dried MPC85S1 was lower than dried MPC85S2. The dried MPC85S1 sample showed the highest a* and b* (Fig. 2). The results for ΔE showed that MPC85S1 and MPC85S2 displayed significant colour changes on drying. The ΔE for MPC85S1 (~20.58) was higher than MPC85S2 (~15.47), indicating that MPC85S1 may have been more prone to heat induced chemical interactions, e.g., Maillard reactions, in comparison to MPC85S2. It appeared that the colour stability of MPC85S2 was higher than MPC85S1 following drying. This is possibly due to it having less...
native WP. Consequently, the higher level of denaturation in sample MPC85S2 may have resulted in a relatively higher colour stability against high temperature treatment of the powders. By increasing the level of WP denaturation, a layer of denatured WP may be generated on the surface of the caseins which may reduce/prevent further reactions resulting in the observed lower extent of colour change for MPC85S2.

Colourimetric analysis of MPC60 reported L* = 88, a* = -1.5 and b* = 13.5 (Meena et al., 2017b). These results correspond to a lower L* and higher a* and b* compared to the samples studied herein. This may be due to differences in lactose content (~28%) of MPC60 in comparison with MPC85 (~< 3%), since drying of samples with a higher amount of lactose may intensify the Maillard reaction, thereby resulting in lower lightness, and higher yellowness and redness. The ratio of casein/WP was previously reported to be an important factor in the development of colour in milk protein solutions. Kelleher et al. (2020) showed by increasing the WP in solution mixtures containing caseins and WPs, that the lightness was reduced upon pre-denaturation. The a* was reported not to be altered upon pre-denaturation but the b* significantly reduced. The lower L* of MPC85S2 (high denaturation) than MPC85S1 (low denaturation) is in agreement with the report of Kelleher et al. (2020). Differences in the nature of the product (e.g., the presence of lactose and lipid in MPC) may account for the different values for a* and b* for the MPCs herein in comparison with the casein/WP mixtures.

The colour index of MPCs is important for their final applications. For instance, using an MPC ingredient with a high susceptibility to colour development on heating at high temperature may lead to significant changes in cheese colour (during processing or melting). It has been shown, for example, on increasing the temperature during the melting of Oaxaca cheese (formulated with 1.5–3.0% MPC) from 125 to 200 °C for 20 min that the lightness of the melted cheese was reduced, while the yellowness increased (Meza-Nieto et al., 2011). Thus, depending on the type of the cheese, specific MPC ingredients may be selected to impart an appropriate final colour. In this study it was seen that the MPC85S2 ingredient was less susceptible to colour development which in turn may influence overall colour formation in final products. The colour values reported above were for MPC powder samples, however, colour differences in reconstituted samples were not visually evident.

### 3.1.3. Thermal stability of MPC85 in powder format

TGA analysis of MPC85S1 and MPC85S2 showed that there were two temperature regions for both samples which displayed weight loss (Fig. 3). The first started at 40 °C and ended 120 °C, and the second started at 250 °C and ended 400 °C. The former region was related to protein denaturation and aggregation and moisture lost from the samples (Chalermtchai et al., 2019), while the second region was related to sample decomposition. The pattern of weight lost was similar for MPC85S1 and MPC85S2. The maximum weight loss for MPC85S1 and MPC85S2 occurred between 300 and 350 °C. Similar trends were reported previously for WPI with maximum mass loss being observed at 390 °C (Chalermtchai et al., 2019). To our knowledge, this is the first report of TGA analysis of MPC.

Dairy proteins are generally not exposed to temperatures > 140 °C. However, with increasing environmental concerns surrounding non-biodegradable plastics, several options are being explored to replace conventional plastics with natural alternatives. One of the alternative applications of dairy proteins is their use in the formulation of biodegradable polymers which may act as a substitute for non-biodegradable polymers such as polyethylene. Therefore, milk proteins have been explored to their ability to produce bio-degradable plastics, especially for food packaging. Heat stability is an important factor for biodegradable polymers. According to Fig. 3, the MPC samples were stable up to ~250 °C which in turn allows them to be considered for polymer applications, such as in food packaging. Chalermtchai et al. (2019) showed that a WPI-based polymer was stable up to 277.8 °C and that a WPC based polymer was stable up to 273.0 °C. The occurrence of decomposition between 315 and 350 °C was reported previously for different type of caseins (Sirioeić, Krehula, Katanieć, & Hrjnak-Murgić, 2016).

Fig. 4 shows the thermal transition profiles for MPC85S1 and MPC85S2 as determined using DSC within the range of 25 to 400 °C. Previously, Haque et al. (2012) reported a thermal transition between 65 and 70 °C for MPC82. The results herein showed that two thermal transition regions related to protein denaturation existed. The first denaturation region occurred between 63 and 75 °C in the case of MPC85S1 while this occurred between 70 and 80 °C in the case of MPC85S2. The transition in this region may be related to unfolding of the WPs which are more heat sensitive than the caseins. The results from

![Fig. 3. Thermogravimetric profiles of milk protein concentrate-85 (MPC85) samples S1 (MPC85S1) and MPC85S2 from 30 to 500 °C with a temperature ramp of 10 °C min⁻¹. Regions #1 and 2 represent the points of maximum weight loss during heating.](image-url)
the first heating stage (25–95 °C) confirmed the higher stability of proteins in MPC85S2 in comparison with MPC85S1, probably due to having less native WP. Holt et al. (1998) previously reported that denaturation of β-lactoglobulin occurs between 70 and 80 °C while Holt et al. (1999b) also reported that the denaturation of α-lactalbumin occurs at ~ 60 °C. No physical changes were observed during cooling of both samples after WP denaturation from 95 to 25 °C (Fig. 4, cooling stage).

A second thermal transition was observed during the second heating stage. This region began at ~ 104 °C and ended at ~ 115–116 °C for both MPC85S1 and MPC85S2. This thermal transition was related to the thermally induced interaction of denatured WP with the caseins which was previously reported by several authors (Siroić et al., 2016; Wu, X., Liu, Y., Liu, A., & Wang, 2017; Farooq, 2019). The formation of complex aggregates between WPs (especially β-lactoglobulin due to its exposed thiol group following denaturation) and caseins (especially κ-casein) is a possible outcome occurring following denaturation (Erdem & Yüksel, 2005; Wijayantri, Bansal, & Deeth, 2014). Heat treatment is reported to mostly affect the surface hydrophobicity of casein micelles (Cenini et al., 2020). The formation of hydrophobic interactions and disulphide bridging are likely to occur in the presence of micelle surface located κ-casein and denatured WPs during heating.

An additional peak appeared in the DSC profile between ~ 250–400 °C, this corresponded to the decomposition of the samples which was already shown in the TGA profiles (Fig. 3). Overall, the results showed that the MPC sample with less native WP (MPC85S2) was more resistant to thermal denaturation.

### 3.2. Technofunctional properties of reconstituted MPC85

#### 3.2.1. Thermal stability of reconstituted MPC85

The temperature at which the HCT of milk proteins is recorded is usually in a range 120–140 °C (Davies & White, 1966). The method of determining HCT may be highly subjective due to assessment of the coagulation time by visual observation (Dumpler et al., 2020). Thermal stability analysis of reconstituted MPC85 (4.2% w/v protein) using an oil bath over a range of temperatures (110–140 °C) showed that both MPC samples were heat sensitive. For sample MPC85S1 on heating at 140 °C, coagulation started at 2.2 min and for MPC85S2 it started at 2.7 min (Fig. 5). This difference indicated that the presence of a lower level of native WP may be the reason for the improved thermal stability for MPC85S2. By reducing the heating temperature, the HCT increased for both samples and in addition the difference between the HCTs of MPC85S1 and MPC85S2 increased. The HCT for MPC85S1 at 110, 120 and 130 °C was 194.8, 59.2 and 20.5 min, respectively. The corresponding values for MPC85S2 were 219.7, 69.0 and 24.1 min, respectively. The data showed that within the temperature range examined herein, the MPC85S1 sample was more heat sensitive than MPC85S2. Furthermore, the relationship between the HCT and the heating temperature was not linear, it was logarithmic. Such a logarithmic relationship was previously reported within the temperature range 105–140 °C (Davies & White, 1966; Dumpler et al., 2020).

The HCT for reconstituted MPC85 (3.5% w/w protein basis) was previously reported to be < 2 min (Crowley et al., 2014b). The HCT of MPC82 (145 °C) has been reported to be 2.54 min (Singh, Prakash, Bhandari, & Bansal, 2019). This HCT value for MPC82 was between the value for MPC85S1 and MPC85S2 reported herein when analysed at 140 °C. The higher HCT value reported by Singh, Prakash, Bhandari, and Bansal (2019) compared to MPC85S1 may be related to the lower protein content in their sample (81.95%, vs 84.17% for MPC85S1). The lower HCT value compared to MPC85S2 may be due to denatured WP in the MPC85S2 sample.

Due to the large variation in the HCT values reported in the literature, it is difficult to make comparisons with the HCT results herein and those in the literature. This is due to differences in the experimental conditions including differences in sample concentration/composition, pH, heating temperature and come up time of the sample to the exact temperature (Sauer & Moraru, 2012; Dumpler et al., 2020). In addition,
HCTs are traditionally determined by visual observation which is inherently subjective and may be best applicable when comparing test samples having similar composition under the same experimental conditions. It therefore may be useful, as suggested by Dumpler et al. (2020), to monitor the heat stability of test samples at different temperatures, pHs and concentrations in order to have a better understanding of their behaviour under different conditions.

By continuing heating at 140 °C, the differences between MPC85S1 and MPC85S2 become more evident as the HIGT of MPC85S1 and MPC85S2 occurred at 18.8 and 19.7 min, respectively (p < 0.05). Aggregation/gelation of skim milk as a result of heat treatment has been associated with the interaction of WPs, especially β-lactoglobulin with κ-casein, through disulphide bridging (Anema, 2018). Furthermore, the heat induced binding of lactoferrin with casein via electrostatic interactions has been reported as a reason for the rapid denaturation of lactoferrin in infant milk formulae (Halabi et al., 2020). However, determination of the exact nature of the heat induced interactions between the denatured WP and the caseins was not within the scope of the present study.

Factors related to seasonal variation, differences in storage conditions and gross composition, which may cause variation in the physicochemical and technofunctional properties of MPCs, are negligible during the comparison of these two MPC samples.

The higher thermal stability of MPC85S2 indicates its greater suitability for several applications such as its incorporation into recombined milk, soups and sauces, and enteral and clinical nutrition products. Crowley et al. (2015) reported that the association of WP with caseins as a result of denaturation during high intensity pasteurisation (95 °C, 45 s) caused the formation of highly stable casein micelles, resistant to the destabilizing conditions such as precipitation of calcium phosphate. Thus, they observed that highly denatured MPC80 is more heat stable than a less denatured sample obtained during normal pasteurisation (72 °C, 15 s). The findings from the HCT of MPC85S1 and MPC85S2 concur with Crowley et al. (2015) who suggested that MPC80 with highly denatured WP (25% of α-lactalbumin and 65% of β-lactoglobulin) had higher heat stability (at 120 °C) compared to low denatured (<5% of α-lactalbumin and β-lactoglobulin).

It should be mentioned that this is the first report on the HIGT for MPCs, showing the lower susceptibility of MPC85S1 to gelation in comparison to MPC85S2 which had a higher level of protein denaturation. This may be of interest for some ingredient applications such as in the formulation of cheese, yoghurt, bakery and confectionary products.

3.2.2. Viscosity analysis

The viscosity of MPC85S1 and MPC85S2 at a concentration of 1.7% (w/v) on a protein basis was similar (µ1.7% = 1.40 ± 0.02 mPa.s). By increasing the concentration to 4.2% (w/v) protein, however, the viscosity of MPC85S2 (µ4.2% = 2.75 ± 0.05 mPa.s) became significantly higher (p < 0.05) than MPC85S1 (µ4.2% = 2.41 ± 0.05 mPa.s). This difference may be related to the higher agglomeration of MPC85S2 particles as a result of extensive WP denaturation.

The viscosity of 1% reconstituted MPC85 at 27 °C was previously reported to be ∼1.52 mPa.s (Shilpashree, Arora, Chawla, & Tomar, 2015). The apparent viscosity of 10% reconstituted MPC80 at 30 °C was reported to be ∼7 mPa.s (Power, Fenelon, O’Malony, & McCarthy, 2020). Higher protein concentration facilitates increased viscosity, probably due to the increase in the volume fraction of suspended MPC particles and hydrodynamic interactions between casein micelles (Wolz & Kulczak, 2015; Sutariya et al., 2017).

Ho et al. (2019) reported that high temperature (100–120 °C) in combination with short time (30 s) treatment increased the viscosity of 12.1% and 17.5% (w/w) protein basis) reconstituted MPC having 87.3% protein (w/w). They showed that a significant increase in the viscosity began for samples heated at 77.9 °C and upwards, thereby, they considered this temperature as the start of the transition from an unfolding to an agglomeration stage. An increase in WP-casein association has been shown to enhance the viscosity of a mixture of WPC-MPC (de Souza et al., 2015). The authors suggested denaturation as a strategy for the development of dairy products requiring high viscosity such as cheeses and yoghurt. The level of WP denaturation and the association of denatured WP with caseins was previously reported to lead to an increase in viscosity in skim milk concentrate (Sutariya et al., 2017). In the present study, it was shown that the more denatured MPC sample (MPC85S2) displayed higher solution viscosity when tested at higher protein concentrations.

3.2.3. Emulsion properties

The emulsions generated with MPC85S1 and MPC85S2 were analysed using laser light scattering particle size analysis. The results showed that the emulsions generated with MPC85S1 and MPC85S2 become unstable as evidenced by a shift to higher mean particle sizes following 4 d storage under the experimental conditions employed herein (Fig. 6). The present results showed that in both MPC samples, the mean particle sizes increased as a function of holding time. It should be mentioned that droplets >3000 µm (which are generated due to flocculation and coalescence) were not recorded/analysed herein. The MPC85S1 emulsion droplets showed higher polydispersity and more rapid flocculation than those generated with MPC85S2.

In the case of MPC85S1, the emulsion sample at day 1 showed two peaks: one between 10 and 100 µm and another >1000 µm. The mean diameter of the emulsion was 29.6 ± 9.5 µm. After 4 days storage at 4 °C, flocculation in the emulsion had increased and two peaks appeared again: one between 10 and 100 µm which shifted to larger diameters with a lower volume (%) compared to the peak present at day 1; the second population of particles was at a similar position as day 1, i.e., >1000 µm. The mean diameter of the emulsion droplets at day 4 was 1128.7 ± 7.9 µm. The increase in the mean diameter was evident as a larger volume (%) of the peak having a larger mean diameter (>1000 µm) for both MPC85S1 and MPC85S2. The emulsions generated with MPC85S1 and MPC85S2 were not analysed for changes in particle size distribution properties of emulsions generated from reconstituted milk protein concentrate-85 (MPC85S) samples (4.2% (w/v) on a protein basis) S1 (MPC85S1) and MPC85S2 with sunflower oil (3:1, v/v) after 1, 4, 14 and 33 d of storage at 4 °C. The plots represent the mean of three measurements.

![Fig. 6. Particle size distribution properties of emulsions generated from reconstituted milk protein concentrate-85 (MPC85S) samples (4.2% (w/v) on a protein basis) S1 (MPC85S1) and MPC85S2 with sunflower oil (3:1, v/v) after 1, 4, 14 and 33 d of storage at 4 °C. The plots represent the mean of three measurements.](image-url)
µm) was recorded. After 14 days, phase separation was visually observed along with creaming and sedimentation. Creaming and sedimentation correspond to the density difference between the dispersed and continuous phases during emulsion destabilisation (Goodarzi & Zendehboudi, 2019). Particle flocculation also continued. Sampling for analysis was performed from the middle of the tube. Therefore, the oil fraction on the top and the sediment fraction at the bottom of the tube did not contribute to the measurement of the mean particle diameter reported (67.4 ± 12.8 µm) at day 14. A similar observation was observed for day 33 with a mean particle diameter of 53.15 ± 1.57 µm.

In the case of sample MPC85S2, the mean particle diameter of the emulsion sample after 24 h was 16.5 ± 0.4 µm and only one peak was observed, showing a monomodal emulsion. After 4 days, flocculation started and two particle populations appeared: one between 10 and 100 µm and another > 1000 µm. The mean diameter size of MPC85S2 emulsion particles arising from these two peaks was 92.7 ± 17.2 µm. At day 14, flocculation increased while two particle populations were evident: one between 10 and 100 µm which had shifted to a larger particle diameter compared to day 4 and with a lower volume ratio (%); and another particle population > 1000 µm. The mean particle diameter of the MPC85S2 emulsion sample at d 14 was 1064.8 ± 143.1 µm, showing that extensive flocculation had occurred. At day 33, phase separation was visually observed along with creaming and sedimentation. Particle flocculation also continued. The sampling was performed from the middle of the tube which still had stabilised MPC85S2 emulsion droplets, without agitation. Sampling for analysis was performed from the middle of the tube. Therefore, the oil fraction on top and the sediments at the bottom of the tube did not take into account for measurement of the mean particle diameter reported (57.78 ± 0.77 µm) at day 33.

The development of bimodal particle size distributions following storage has been linked to the clustering of oil droplets through bridging flocculation (Rosenberg & Lee, 1993). Euston and Hirst (1999) reported the development of bimodal distributions during storage of MPC85-soya oil emulsions where the majority of the droplets were in the range of 1–100 µm after d storage at 20 °C. Bimodal particle distributions were also reported for MPC75-rapseed oil emulsions, i.e., within the ranges 0.090–0.255 and 0.400–2.670 µm. Bimodal distribution was also reported for MPC85 (2%)-canola oil emulsions (Gopirajah et al., 2020). Generally, smaller droplet size emulsions are less prone to phase separation (Ye, 2011). Formation of the larger sized particles was reported to be associated with lipid globule coalescence and protein aggregate attachment to the lipid droplets (Dybowska, 2008).

Several strategies have been employed for the improvement of the stability of emulsions generated by MPC. These include, protein hydrolysis using chymotrypsin and trypsin (Banach, Lin, & Lamsal, 2013), ultrasonication treatment during MPC manufacture (Yanjun et al., 2013) and modification of the mineral equilibrium (Ye, 2011). There are conflicting reports on the impact of protein denaturation on the emulsion properties of dairy proteins. Previously, Euston and Hirst (1999) showed that the protein aggregation may increase the stability of emulsions perhaps due to higher bulk viscosity associated with more denatured protein systems. In addition, protein pre-denaturation has been shown to enhance the stability of MPC75 emulsions (Dybowska, 2008). Denaturation of WP (> 70 °C) has previously been shown to enhance its emulsion properties, because unfolding of WP and subsequent exposure of WP reactive sites increases its surface hydrophobicity (Liu et al., 2012). Recently, Malek, Matia-Luna, Ye, and Golding (2013) reported that an extensive denaturation of MPC85 obtained from a heating process (120 °C, 10 min) reduced the emulsion properties due to changes in the adsorption behavior of proteins as a result of heat induced interactions.

The level of WP denaturation and the level of the subsequent interactions of the denatured WP with the casein micelles is considered a key factor for emulsion properties. These interactions impact the protein surface properties, e.g., protein hydrophobicity, which are the key factors for the development of high quality emulsions. The results in this study would indicate that the MPC with a lower level of native WP resulted in the generation of MPC emulsions with a higher stability. Development of a greater understanding of the optimum level of denatured WPs required in MPC stabilised emulsions is recommended in order to develop new food emulsion systems with improved properties.

3.2.4. Potential applications of MPC

The ethanol stability of reconstituted MPC (4.2% protein (w/v)) samples MPC85S1 and MPC85S2 was shown to be similar. Both samples were stable in the range of ethanol concentrations examined herein, except at the ethanol concentrations > 90% (v/v). At this point, flocculation occurred for both MPC85S1 and MPC85S2. The ethanol stability of an MPC82 suspension was previously reported to be ~ 50% (v/v) (Lin et al., 2018). Differences in the gross composition and variations in the manufacturing parameters may account for the differences in the results reported by Lin et al. (2018) compared to the data herein. The ethanol stability of different dairy ingredients including skim milk powder, native phosphocasein, calcium caseinate, calcium-reduced phosphocasein and sodium caseinate was determined by Lin, Kelly, O’Mahony, and Guinee (2016). The stability was ~90% at neutral pH for all samples. The data for samples MPC85S1 and MPC85S2 herein are in agreement with the observations by Lin et al. (2016). The aggregation of micellar casein occurs more rapidly in the presence of ethanol, mainly via the collapse of the ‘airy layer’ attached to κ-casein (Horne & Parker, 1983; Huppertz & de Kruijff, 2007). No data on the impact of WP denaturation on the ethanol stability of MPC appears to be available in the literature. However, WP denaturation at the levels present in the samples studied herein did not change the ethanol stability of MPC85.

The acid-buffering index of MPC85S1 was shown to be 0.026 ± 0.001, while for MPC85S2 it was 0.033 ± 0.001. The higher buffering capacity of MPC85S2 may be related to higher phosphate (Meletaharyiil, Patel, & Huppertz, 2015) release to the aqeous phase of reconstituted MPC, potentially as a result of conformational changes in the MPC85S2 proteins. Li and Corredig (2014) listed a number of factors which may impact the acid-buffering capacity of concentrated milk protein, one of which was WP denaturation. Some ionizable groups that are inaccessible in proteins may become accessible following denaturation, thereby changing the buffering capacity of the proteins (Salain, Mietton, & Gaucheron, 2005). Alteration in pH often occurs in the dairy industry (e.g., during production of yoghurt and cheese, and during heat treatment over 90 °C for several min). Protein buffering capacity is associated with the sequence, structure and the environmental conditions of the protein (Salain et al., 2005). The maximum buffering capacity of WP and caseins was previously indicated to occur in the pH range of 3.0–4.0 and 5.0–5.5, respectively. Thereby in the pH range of the experiment herein (pH 4.0–7.0), it seems that casein is the major contributor to the buffering capacity. The acid-buffering index of skim milk powders, WP and Na-caseinate have been reported to be ~ 0.02, 0.03 and 0.06, respectively (Kim, Oh, & Imm, 2018). The acid-buffering index of MPC60 was previously reported to be > 0.02 (Meena et al., 2017b). The relative contribution of salt, caseins and WP to the buffering capacity of milk has been reported to be 58.6, 36 and 5.4%, respectively (Salain et al., 2005). MPC has been used for its high-buffering capacity in the formulation of probiotic yoghurt to prevent post-acidiﬁcation (Moghaddas Kia, Ghasempour, Ghanbari, Pirmohammadi, & Ehsani, 2016). The results herein indicated a potentially greater capability of MPC85S2 for supplementation in fermented and long shelf-life products while maintaining pH. MPC with high buffering capacity and high ethanol stability has potential in the control of post-acidiﬁcation in fermented products.

In this study, it was shown that the properties of MPC powders and reconstituted MPC samples with two different levels of WP denaturation varied. This suggests the possibility of employing MPC samples with various levels of WP denaturation for different applications. One important parameter for food powders is their flowability. As MPC powders are stored in bags and in silos; elucidation and control of their...
flow behavior during storage, handling and processing are important. The flowability characteristics of the MPC powders may be attributed to their small particle size, high specific surface area and high protein–protein interactions. In addition, it is desirable that some products such as infant formula are highly flowable. Thermal stability is another important factor for MPC used in formulated food products. MPCs with high thermal stability are potentially more appropriate for use in the formulation of products such as recombined milk, soups and sauces and clinical nutrition where thermal treatment is an important part of the process. High emulsification properties are also desirable for the utilisation of MPC in, e.g., soups and sauces, ice cream, confectionary and coffee whitener. High viscosity in MPCs is also important for its application in cheese, yogurt and confectionary products.

4. Conclusions

There is a need to continually develop dairy protein ingredients with enhanced technofunctional properties in order to improve and expand their end uses and applications. This study demonstrates that the functional properties of MPCs having similar protein contents can be significantly different depending on differences in the level of WP denaturation. This is particularly relevant for applications/products which require high temperature treatments following supplementation with MPC85. The methods used provide evidence of the impact of WP denaturation on the flowability, emulsification, colour stability, thermal stability, viscosity and acid-buffering capacity. All of these properties are highly relevant in the formulation of different food products using MPC. In the present study, the MPC85 sample with a higher level of WP denaturation was also associated with a higher viscosity, permeability, compressibility and cohesiveness. Furthermore, the MPC sample with the higher level of denaturation had higher colour and thermal stability and a slower rate of emulsion flocculation. In addition, a higher acid-buffering capacity, a property relevant to food systems which undergo fermentation, was observed in the MPC sample having the higher level of WP denaturation. This study is relevant for dairy/food scientists in order to understand the potential behaviour of MPCs during different applications. Furthermore, the results of this study are relevant for the dairy ingredient manufacturing industry in the development of dairy-based protein enriched ingredients with targeted functionality. The results presented herein indicate that modification of the level of WP denaturation leads to changes in the technofunctional properties in MPC85. Thus, knowledge on the level of WP denaturation has important consequences in understanding the properties of MPC ingredients. The data given herein is representative of some important technofunctional properties. However, further analyses such as those associated with MPC interactions with the aqueous phase (e.g., powder wettability and solubility), foaming properties, etc, need to be performed in order to better understand the relationship between WP denaturation in MPC and its functionality. Additionally, it is proposed that a series of MPC samples with a wider range of WP denaturation (i.e., more than two levels of WP denaturation) be generated and investigated for the characteristics assessed herein in order to further elucidate, and ultimately optimise, the impact of WP denaturation on the technofunctional properties of MPC.

Declaration of Competing Interest

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

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