particle surface design for enhanced reconstitution of Fat-based food powders

Diamanto Angelopoulou1, Vincent Meunier2, Laurent Forny3, Gerhard Niederreiter2, Stefan Palzer4, Agba D. Salman1

*1 Department of Chemical and Biological Engineering, University of Shefﬁeld, S1 3JD, UK*

*2 Nestlé Research, Vers-chez-les-blanc, 1000 Lausanne 26, Switzerland*

*3 Nestlé Product Technology Center, Route de Chavornay 3, 1350 Orbe, Switzerland*

*4 Nestlé SA, Avenue Nestlé 55, 1800 Vevey, Switzerland*

1. Introduction

The surface characteristics of food powders play a significant role in driving the powder reconstitution properties. Powder reconstitution involves four distinct physical steps which may overlap: wetting, sinking, dispersion, and – in the case of soluble powders – dissolution [1].

The first interaction of powder with water, known as wetting, is greatly influenced by the particle surface composition [2]. As demonstrated by Kammerhofer et al. [3], powder wetting can be significantly decelerated in the presence of hydrophobic surfaces. In the case of spray-dried milk powders, hydrophobic compounds are often overrepresented on the particle surface compared to the bulk. For whole milk powder (WMP) in particular, a predominance of fat on the particle surface has been reported in the literature [4–7]. Different hypotheses exist which aim to explain the component redistribution occurring during spray drying, including possible migration of hydrophobic compounds to the particle surface during drying and phase separation during atomization [5,7,8]. Wetting of WMP is influenced by the physical state of surface fat, which depends on the reconstitution temperature [9,10]. Kim et al. [9] showed that WMP could not be wetted within a reasonable time (> 15 min) in “cold” water (10 to approx. 37°C).

In the present study, we investigate a method for improving the reconstitution performance of WMP in “cold” water. This method involves coating of WMP with micronized lactose (i.e. fine lactose powder, < 10 μm) by means of ordered dry mixing (also known as interactive mixing). In ordered mixing, a coarse powder is mixed with a relatively fine one [11]. If the adhesive forces (van der Waals and electrostatic forces) between the large and fine particles are greater than the gravitational and cohesive forces of the fine particles, the fine particles are attached onto the surface of the large ones and form a coating layer [12]. For the adhesive forces to prevail, a size difference between the guest and host particles of at least one to two orders of magnitude is typically required [13], and the size of the fine particles must not exceed a few micrometres [12].

In particle coating, along with the hydrophilicity of the particle surface, the dissolution kinetics of the coating material is another important parameter to consider. The dissolution rate of solid lactose depends on its molecular organization [14]. As explained by Palzer [15], when soluble amorphous materials are immersed into water, water is diffusing while dissolving, leading to viscosity build-up within and between the particles. On the other hand, the dense packing of molecules in the case of crystalline materials does not allow for diffusion of water into the particle, and dissolution occurs layer by layer. The large solvent-accessible surface area of amorphous lactose makes its dissolution considerably faster than that of crystalline lactose.

Dry coating has been previously used in the pharmaceutical industry as a method to improve the rehydration properties of active ingredients [16,17]. However, the application of such a technique in the food industry, and particularly as a tool for improving the reconstitution of fat-based food powder systems, is novel. This study aims to provide insight into the reconstitution mechanisms of dry coated fat-based food powders at 21°C, and determine the correlation between surface chemical composition, physical solid state of coating material and powder reconstitution performance.

1. Materials and Methods
   1. Materials

The materials used as host particles were non-agglomerated WMP (n-WMP) and agglomerated WMP (a-WMP). Non-agglomerated WMP was supplied by LacPatrick Dairies, Ireland (aw = 0.24 at 20°C). Agglomerated WMP was supplied by Nestlé Research, Switzerland (aw = 0.13 at 20°C).

The coating materials were coarse α-lactose monohydrate, micronized α-lactose monohydrate, and micronized spray-dried lactose. Micronized α-lactose monohydrate (Lactochem Microfine) and coarse α-lactose monohydrate (Pharmatose 200M) were supplied by DFE Pharma, the Netherlands. Micronized spray-dried lactose was prepared by spray drying a lactose solution in a Mobile Minor spray dryer (GEA, Denmark) with a co-current two-fluid nozzle (1 mm orifice diameter). The liquid feed was a 20% (w/w) aqueous lactose solution (70°C). The atomizing air pressure and feed flow rate applied were 0.5 bar and 4.5 kg/h, respectively. Flow rate of the drying gas was approximately 100 kg/h. The Tinlet and Toutlet were 160°C and 90°C, respectively. The spray-dried lactose powder (aw = 0.12 at 20°C) was subsequently micronized using a J-70 jet mill (Tecnologia Meccanica, Italy).

To determine the physical solid state of micronized spray-dried lactose, X-ray diffraction (XRD) was performed. The instrument used was a MiniFlex 600 (Rigaku, Japan). The measurement was conducted at a speed of 10°/min and a resolution of 0.02°. The X-ray source was copper (k-alpha 1.54 Å). Micronized spray-dried lactose exhibits no sharp peaks typical of crystalline materials (unlike α-lactose monohydrate) and can therefore be classified as amorphous (see Figure 1).

Diagram, histogram

Description automatically generated

Figure 1. X-ray diffraction of micronized α-lactose monohydrate (from DFE Pharma) and micronized spray-dried lactose (homemade)

The particle size distributions of the different powders were obtained using Camsizer® XT (Retsch Technology, Germany) at 180 kPa dispersion pressure for the n-WMP and lactose powders, and at 60 kPa for a-WMP (to prevent breakage of the agglomerates). Prior to use, the coarse α-lactose monohydrate was sieved to obtain a particle size distribution similar to that of n-WMP. The d-values (d10, d50 & d90), which represent the intercepts for 10%, 50% and 90% of the cumulative volume of the four powders, are presented in Table 1 (average ± 95% confidence interval).

Table 1. Particle size distributions of n-WMP, a-WMP, coarse α-lactose monohydrate, crystalline micronized lactose, and amorphous micronized lactose

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | n-WMP | a-WMP | Coarse α-lactose monohydrate | Crystalline micronized lactose | Amorphous micronized lactose |
| d10 (μm) | 31 ± 1 | 62 ± 2 | 29 ± 6 | 4 ± 0 | 3 ± 0 |
| d50 (μm) | 80 ± 6 | 162 ± 6 | 77 ± 7 | 6 ± 0 | 5 ± 0 |
| d90 (μm) | 153 ± 5 | 352 ± 26 | 144 ± 9 | 9 ± 0 | 6 ± 0 |

* 1. **Surface morphology**

All samples were visualized using scanning electron microscopy (SEM). The SEM instrument used was an InTouchScope from JEOL, Japan. Prior to SEM visualisation, a gold layer was applied on the sample surface using a sputter coater (Agar Scientific, UK) to minimize charging effects. The pressure and current applied for the gold sputtering were 0.04 mb and 40 mA, respectively. The target to specimen distance was 25 mm and the application time was 12 s.

* 1. **Powder mixing**

Powder mixing was performed in a high-shear mixer (Hotpoint 1000W, USA) comprising a custom-made 45° pitched 3-blade impeller (20 cm diameter). The mixing speed and time were 120 rpm and 5 min. The batch size of the mixture was 200 g. The conditions were determined after preliminary experiments on the homogeneity and quality of mixing. No attrition phenomena or changes in the particle size distribution of WMP were observed at the specified mixing parameters. Micronized lactose was applied at 5% and 10% (w/w) in the n-WMP mixtures, and at 1% and 2% (w/w) in the a-WMP mixtures.

* 1. Reconstitution analysis

The custom-made setup used in the reconstitution experiments is presented in Figure 2. It consists of an unbaffled glass vessel (7 cm internal diameter) and a steel feeding tube (5 cm internal diameter) with a plate at the bottom for instant feeding of the powder. The distance between the feeding tube opening and the surface of the liquid is 5 cm. A conductivity probe (Jenway 3540 model, k value 0.111 cm− 1 at 25°C, UK), placed vertically to the vessel using a fitting, was used to monitor the dissolution. Agitation was performed using a magnetic stirring bar (cylindrical PTFE, 25 mm), and the agitation speed was controlled using a stirring hotplate (Dragon Lab, MS7-H550-Pro, China). A video camera (1920 x 1080 pixels, 30 fps), positioned from the top, was used to monitor powder sinking. In all reconstitution experiments, 200 ± 0.1 ml deionized water and 4 ± 0.01 g of powder were used. The water temperature was 21 ± 1°C and the agitation rate applied was 400 rpm.

Diagram

Description automatically generated

Figure 2. Reconstitution setup

The reconstitution properties assessed in this study are the sinking time (tsink), % dissolution over time, and the t90. The tsink is defined as the time interval between the moment the powder is introduced onto the water surface (by opening the moving plate at the bottom of the feeding tube) and when the powder is fully submerged into the liquid. The t90 is the time to achieve 90% dissolution, meaning the time when 90% of the maximum conductivity value for each sample is reached. The reconstitution experiments were performed ten times and the error bars represent 95% confidence intervals. An example reconstitution profile is presented in Figure 3. As it can be observed, there exist cases of slow-sinking powders where tsink > t90.

A picture containing chart

Description automatically generated

Figure 3. Reconstitution profile example

The reconstitution of pure lactose powders was measured using the same setup and conditions as described above, however in this case dissolution was monitored using a refractive index probe (FRI-NP, Fiso, Canada) as lactose is not conductive. Videos of the reconstitution of pure lactose powders were taken from the side, as the turbidity of the liquid upon reconstitution was low (unlike for WMP), thereby allowing for observation of the interface between powder and water.

* 1. **Apparent contact angle**

Determination of the true contact angle is only possible for inert materials with perfectly smooth and chemically homogeneous surfaces. In the case of food powders, properties such as surface roughness, heterogeneous composition and swelling of components can influence the contact angle [2,18,19]. Therefore, in this study, the term “apparent” contact angle was adopted. In order to prevent a potential damage to the coating and re-distribution of the (metastable) surface fat, as well as capillary penetration phenomena, a thin powder layer was used instead of a tablet as the substrate for droplet spreading (see Figure 4). The thin layer was prepared by sprinkling powder on a double-sided tape (θ = 85°) and removing the excess material [20].

The setup used for the apparent contact angle measurements was an FTA1000B goniometer (First Ten Angstroms, USA). Droplets of deionized water at 21 ± 1°C (7 μl maximum volume) were deposited on the powder layer (3 mm dropping height) and the apparent contact angle was extracted using the instrument software. Ten individual measurements were conducted and the average and 95% confidence intervals after 45 s are reported. The 45 s was considered a relevant timescale for the current application [21].



Figure 4. Apparent contact angle setup

The apparent contact angle of coated powders was also predicted by the Cassie-Baxter equation (Eq. 1) using the fractions of the two components (WMP and micronized lactose) on the particle surface, similar to the model described by Mundozah et al. [22]. This model assumes that all particles are spherical, the surface is smooth, and the presence of air is neglected.

(1)

where is the apparent contact angle of WMP, and the apparent contact angle of micronized lactose.

The WMP surface area coated by micronized lactose () is calculated by:

(2)

where is the projected area of guest particles (micronized lactose), and the surface area per unit volume of the host particles (WMP). The and variables are given by:

(3)

(4)

where is the volume fraction of WMP, is the d50 of WMP, and is the d50 of micronized lactose. The volume fractions were calculated using the mass of each powder in the mixture and the respective true densities (WMP: 1280 kg/m3, crystalline lactose: 1550 kg/m3 – values from Schuck et al. [23]).

1. Results and discussion
   1. **Surface morphology of uncoated and coated powders**

SEM images of the raw materials are presented in Figure 5. n-WMP has a relatively smooth surface and consists of single particles or agglomerates of a few particles, while larger agglomerates can be observed in the case of a-WMP. No apparent differences exist between the two types of micronized lactose.

A picture containing map

Description automatically generated

Figure 5. SEM images of n-WMP, a-WMP, crystalline micronized lactose, and amorphous micronized lactose

The surface morphologies of coated n-WMP and a-WMP are shown in Figure 6 and Figure 7. Presence of fine lactose particles can be observed on the particle surface of all coated powders, and surface coverage appears larger with increasing concentration of the coating material. No apparent differences can be observed between the powders coated with crystalline and amorphous micronized lactose.

Map

Description automatically generated

Figure 6. SEM images of coated n-WMP at 5/10% (w/w) crystalline/amorphous micronized lactose (ML)

Map

Description automatically generated with medium confidence

Figure 7. SEM images of coated a-WMP at 1/2% (w/w) crystalline/amorphous micronized lactose (ML)

* 1. Reconstitution of pure micronized lactose powders

The reconstitution properties of pure micronized lactose powders are presented in Figure 8. These results show that sinking is significantly faster for the crystalline powder. As the two micronized lactose types do not differ significantly in terms of apparent contact angle, the sinking time discrepancy may be explained by another mechanism; by observing the video time-lapses, it is proposed that the longer floating of the amorphous powder is related to the development of a viscous layer at the powder-water interface that prevents water from rising into the inter- and intraparticle voids of the powder bed. This quick viscosity build-up is related to the molecular organization of the powder which allows for diffusion of water into its matrix and a fast dissolution [15]. Similar effects of local viscosity build-up have been reported by Mitchell et al. [1].

Table

Description automatically generated with low confidence

Figure 8. Reconstitution properties of pure micronized lactose powders, crystalline (left) and amorphous (right)

* 1. Reconstitution of coated non-agglomerated WMP (n-WMP)
     1. **Apparent contact angle**

The measured and predicted apparent contact angle values of coated n-WMP are presented in Table 2. As there were no differences in terms of apparent contact angle between the two micronized lactose states (see Figure 8), only crystalline ML was used in this section. For the calculations, the average measured apparent contact angles of n-WMP and micronized lactose were used. Good agreement between the measured and predicted values can be observed.

Table 2. Apparent contact angle (measured and predicted) of n-WMP, crystalline micronized lactose, and coated n-WMP at 5/10% (w/w) crystalline micronized lactose

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | n-WMP | Crystalline micronized lactose | n-WMP + crystalline micronized lactose | |
| 5% (w/w) | 10% (w/w) |
| Apparent contact angle (°)  measured | 50 ± 3 | 19 ± 2 | 44 ± 2 | 42 ± 2 |
| Apparent contact angle (°)  predicted | - | - | 45 | 40 |

* + 1. Effect of crystalline micronized lactose coating on reconstitution

Addition of crystalline micronized lactose on the surface of n-WMP results in a significant enhancement of the reconstitution kinetics (Figure 9). For the concentration range explored, the higher the crystalline micronized lactose content, the faster the reconstitution is.

Chart

Description automatically generated

Figure 9. Reconstitution of uncoated and coated n-WMP. (a) n-WMP + 0/5/10% (w/w) crystalline micronized lactose (ML), (b) n-WMP + 0/5/10% (w/w) amorphous micronized lactose (ML). Dashed lines and values of the same colour represent the tsink of each material.

The reconstitution improvement is primarily attributed to a decrease in the sinking time as a result of the micronized lactose coating. A decrease in the tsink of over 70% compared to pure n-WMP can be observed at 10% (w/w) crystalline micronized lactose. Video time-lapses of the liquid surface at 700 s from the beginning of reconstitution (see Figure 10) show that n-WMP is almost intact on the water surface, while the 10% crystalline ML sample has fully submerged into the water.

A picture containing shape

Description automatically generated

Figure 10. Reconstitution time-lapse images of uncoated and coated n-WMP (5/10% w/w crystalline/amorphous micronized lactose) at t = 700 s

To better understand the effect of lactose on the sinking behaviour of the mixtures, an additional experiment was performed, where n-WMP was mixed with coarse α-lactose monohydrate using the same mixing parameters as for micronized lactose. Mixing of n-WMP with lactose of equal particle size is expected to lead to a “random” mixture, with no surface effects or adhesive forces [11].

As seen in Figure 11, there is no significant difference between n-WMP and n-WMP mixed with 10% (w/w) coarse lactose in terms of sinking time. This suggests that the sinking enhancement can only be linked to the surface effect of micronized lactose. The surface effect occurs as a result of the size difference between the two powders (adhesive forces > cohesive forces) and the fine nature of micronized lactose (adhesive forces > gravitational forces). The hydrophilic nature of the lactose coating leads to enhanced surface hydrophilicity of WMP and a decrease in the apparent contact angle (see Table 2). This, in turn, has an impact on the capillary forces acting at the powder-water interface which can influence the sinking behaviour of such a powder system, as explained by Dupas et al. [21]. Apart from the contact angle, other parameters which can influence the sinking kinetics are the particle size and density [21,24]. However, for the size range of these powders, where the ratio of gravitational to capillary forces is ≪0.1, capillary forces are expected to play a far more important role in determining if the particle will sink or float.

Chart, bar chart

Description automatically generated

Figure 11. Sinking time of n-WMP, n-WMP + 10% (w/w) coarse α-lactose monohydrate, and n-WMP + 10% (w/w) crystalline micronized lactose

* + 1. **Effect of amorphous micronized lactose coating on reconstitution**

When amorphous micronized lactose is added on n-WMP, reconstitution enhancement is not proportional to the coating concentration (Figure 9). At a relatively low amorphous micronized lactose content (5%), the reconstitution improvement is significant, similar to the case of crystalline ML. However, increasing the concentration to 10% (w/w) has little, if any, further effect. This phenomenon is related to the viscosity build-up mechanisms discussed in §3.2. It is suggested that at a relatively high amorphous ML content, viscosity build-up phenomena caused by quick dissolution of the coating material hamper capillary penetration and delay the sinking. When crystalline ML is used as the coating material, the increase in local viscosity is not expected to be as pronounced, thereby leading to a faster sinking.

The differences in terms of sinking behaviour due to the micronized lactose state can also be observed using time-lapse images of the videos taken during reconstitution (see Figure 10). At 700 s from the beginning of reconstitution, the 10% (w/w) crystalline micronized lactose sample has fully submerged into the water, while some of the 10% (w/w) amorphous micronized lactose sample can still be observed on the liquid surface.

* 1. Reconstitution of coated agglomerated WMP (a-WMP)

Agglomeration is a well-known technique for improving the reconstitution of dairy powders [25]. In the present study, coating was performed on agglomerated WMP too, so as to examine if reconstitution enhancement is possible for larger and more easily reconstituted host powders. In the case of a-WMP, lower micronized lactose concentrations were applied (1% and 2% w/w) as the surface area of the host powder is smaller, thereby requiring less coating material to achieve the desired surface coverage (i.e. coverage that leads to a decrease in reconstitution time of the same magnitude as for n-WMP).

Addition of crystalline micronized lactose up to 2% results in a significant increase in the reconstitution rate of a-WMP, related to a decrease in sinking time (Figure 12). Mixing of a-WMP with 1% crystalline micronized lactose leads to a decrease in sinking time of more than 50%. At 2% crystalline micronized lactose, sinking occurs in less than 15 s, and a decrease in t90 of approximately 50% compared to the original value at 0% micronized lactose is achieved.

When a-WMP is coated with amorphous micronized lactose, a different trend is observed (see Figure 12). Although the 1% coating leads to a significant increase in the reconstitution rate, increasing the concentration to 2% does not have a significant further impact. This phenomenon can be associated with viscosity build-up effects due to quick dissolution of the amorphous coating, which become pronounced at a relatively high coating content. This observation is in line with the n-WMP results.

Chart, scatter chart

Description automatically generated

Figure 12. Reconstitution of uncoated and coated a-WMP. (a) a-WMP + 0/1/2% (w/w) crystalline micronized lactose (ML), (b) a-WMP + 0/1/2% (w/w) amorphous micronized lactose (ML). Dashed lines and values of the same colour represent the tsink of each material.

1. Conclusion

This study investigated the effect of a micronized lactose coating on the reconstitution behaviour of non-agglomerated and agglomerated WMP at 21°C. Coating was performed by means of ordered dry mixing. The results showed that deposition of micronized lactose on the surface of WMP at the concentration range explored (up to 10% w/w for non-agglomerated WMP and up to 2% for agglomerated WMP) leads to a significant decrease in the reconstitution time. Significant improvement was already observed at 5% micronized lactose for non-agglomerated WMP and 1% for agglomerated WMP. The reconstitution enhancement was attributed to a decrease in the sinking time, correlated with a decrease in the apparent contact angle as a result of the hydrophilic coating treatment. It was also demonstrated that the reconstitution performance of coated WMP is influenced by the state of micronized lactose used as coating material (crystalline/amorphous). When crystalline micronized lactose was applied, the higher the coating content, the faster the reconstitution was. In the case of amorphous micronized lactose, a delay in the sinking at a relatively high coating content was observed. This was attributed to viscosity build-up phenomena, caused by quick dissolution of the amorphous lactose coating, which could hamper capillary penetration and lead to a decrease in the sinking rate. The reconstitution enhancement as a result of the coating treatment and the differences observed related to the crystalline vs. amorphous state of the coating material were significant for both non-agglomerated and agglomerated WMP.

This study provided insight into the relationship between surface properties and powder reconstitution which should be considered when particle coating is used to improve the reconstitution performance of fat-based food powders.

**ACKNOWLEDGMENTS**

The authors would like to thank Teresa Kurtz for performing the jet-milling and Delphine Pasche for the X-ray diffraction analysis.

**FUNDING**

This work was funded by the Société des Produits Nestlé, Vevey, Switzerland.

References

[1] Mitchell WR, Forny L, Althaus TO, Niederreiter G, Palzer S, Hounslow MJ, et al. Mapping the rate-limiting regimes of food powder reconstitution in a standard mixing vessel. Powder Technology 2015;270:520–7.

[2] Forny L, Marabi A, Palzer S. Wetting, disintegration and dissolution of agglomerated water soluble powders. Powder Technology 2011;206:72–8.

[3] Kammerhofer J, Fries L, Dupas J, Forny L, Heinrich S, Palzer S. Impact of hydrophobic surfaces on capillary wetting. Powder Technology 2018;328:367–74.

[4] Nijdam JJ, Langrish TAG. The effect of surface composition on the functional properties of milk powders. Journal of Food Engineering 2006;77:919–25.

[5] Kim EH-J, Chen XD, Pearce D. Surface composition of industrial spray-dried milk powders. 2. Effects of spray drying conditions on the surface composition. Journal of Food Engineering 2009;94:169–81.

[6] Murrieta-Pazos I, Gaiani C, Galet L, Scher J. Composition gradient from surface to core in dairy powders: Agglomeration effect. Food Hydrocolloids 2012;26:149–58.

[7] Foerster M, Gengenbach T, Woo MW, Selomulya C. The impact of atomization on the surface composition of spray-dried milk droplets. Colloids and Surfaces B: Biointerfaces 2016;140:460–71.

[8] Nuzzo M, Sloth Overgaard J, Bergenståhl B, Millqvist-Fureby A. The morphology and internal composition of dried particles from whole milk—From single droplet to full scale drying. Food Structure 2017;13:35–44.

[9] Kim EH-J, Chen XD, Pearce D. Effect of surface composition on the flowability of industrial spray-dried dairy powders. Colloids and Surfaces B: Biointerfaces 2005;46:182–7.

[10] Mitchell WR, Forny L, Althaus T, Niederreiter G, Palzer S, Hounslow MJ, et al. Tracking of powder lump formation and dispersion with the use of FBRM technology and video recordings. Powder Technology 2020;367:10–9.

[11] Hersey JA. Ordered mixing: A new concept in powder mixing practice. Powder Technology 1975;11:41–4.

[12] Saleh K, Guigon P. Chapter 7 Coating and encapsulation processes in powder technology. vol. 11. Elsevier Science B.V.; 2007.

[13] Pfeffer R, Dave RN, Wei D, Ramlakhan M. Synthesis of engineered particulates with tailored properties using dry particle coating. Powder Technology 2001;117:40–67.

[14] Li R, Lin D, Roos YH, Miao S. Glass transition, structural relaxation and stability of spray-dried amorphous food solids: A review. Drying Technology 2019;37:287–300.

[15] Palzer St. The relation between material properties and supra-molecular structure of water-soluble food solids. Trends in Food Science & Technology 2010;21:12–25.

[16] Nyström C, Westerberg M. The use of ordered mixtures for improving the dissolution rate of low solubility compounds. J Pharm Pharmacol 1986;38:161–5.

[17] de Villiers MM, Lötter AP, van der Watt JG. Influence of surfactants and interactive mixing on the cohesive properties of a poorly wettable solid. Powder Technology 1993;75:159–65.

[18] Dupas J, Verneuil E, Ramaioli M, Forny L, Talini L, Lequeux F. Dynamic Wetting on a Thin Film of Soluble Polymer: Effects of Nonlinearities in the Sorption Isotherm. Langmuir 2013;29:12572–8.

[19] Dupas J, Verneuil E, Van Landeghem M, Bresson B, Forny L, Ramaioli M, et al. Glass Transition Accelerates the Spreading of Polar Solvents on a Soluble Polymer. Phys Rev Lett 2014;112:188302.

[20] Puri V, Dantuluri AK, Kumar M, Karar N, Bansal AK. Wettability and surface chemistry of crystalline and amorphous forms of a poorly water soluble drug. European Journal of Pharmaceutical Sciences 2010;40:84–93.

[21] Dupas J, Forny L, Ramaioli M. Powder wettability at a static air–water interface. Journal of Colloid and Interface Science 2015;448:51–6.

[22] Mundozah AL, Cartwright JJ, Tridon CC, Salman AD, Hounslow MJ. Wetting of binary powder mixtures. International Journal of Pharmaceutics 2019:118770.

[23] Schuck P, Jeantet R, Dolivet A. Analytical Methods for Food and Dairy Powders. John Wiley & Sons, Chichester, UK; 2012.

[24] Mitchell WR, Forny L, Althaus T, Niederreiter G, Palzer S, Hounslow MJ, et al. Surface tension-driven effects in the reconstitution of food powders. Chemical Engineering Research and Design 2019;146:464–9.

[25] Chever S, Méjean S, Dolivet A, Mei F, Den Boer CM, Le Barzic G, et al. Agglomeration during spray drying: Physical and rehydration properties of whole milk/sugar mixture powders. LWT - Food Science and Technology 2017;83:33–41.