Co-spray drying whey protein isolate with polysaccharides provides additional lubrication impacting the sensory profile of model beverages

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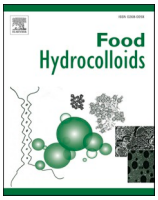

Co-spray drying whey protein isolate with polysaccharides provides additional lubrication impacting the sensory profile of model beverages

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ABSTRACT

For older adults, whey protein is associated with negative sensory attributes, including undesirable mouthfeel qualities, that limit consumption and acceptance. Previous work suggests that increased lubrication may have the ability to reduce whey protein-associated mouthdrying, a driver for disliking, by limiting interactions of whey protein with salivary proteins and mucin. This was investigated in the current study by co-spray drying whey protein with combinations of maltodextrin, xanthan gum and/or guar gum; the resulting powders were used to make 10% suspensions. The particle size, zeta potential, rheological and tribological profiles of these suspensions were measured. It was shown that co-spray drying whey protein with guar gum led to a reduction in instrumental friction, irrespective of changes in viscosity. These samples were perceived as significantly more mouthcoating and smooth when assessed by a trained sensory panel. Contrastingly, suspensions containing xanthan gum showed increased viscosity and enhanced shear thinning compared with whey protein, but no change in instrumental friction at higher sliding speeds. This may be a result of a larger particle size, representing increased aggregation in samples containing xanthan gum. There was no significant difference in mouthdrying or slipperiness perception between the suspensions. These findings suggest that the incorporation of guar gum has the capacity to reduce oral friction and impact mouthfeel in whey protein model beverages. This should be taken forward into temporal sensory trials to further investigate the effects of additional lubrication.

1. Introduction

1.1. The need for additional lubrication of whey protein

Adequate protein intake is important in maintaining the health of older adults by enhancing immune function and reducing the risk of fracture, frailty, cognitive decline, and sarcopenia development (Smith, Clegg, & Methven, 2022). In the UK, the reference nutrient intake for older adults is the same as the general population at 0.75 g/kg/day (Scientific Advisory Committee on Nutrition, 2011). However, the European Society for Clinical Nutrition and Metabolism (ESPEN) suggest that 1.0–1.2 g/kg/day may be more appropriate for older adults (Deutz et al., 2014). It has been reported that older adults repeatedly fall short of these guidelines: in a UK study of 256 older adults, 35.6% consumed less than 0.75 g/kg/day of protein and 81.6% consumed less than the ESPEN recommendation (Morris et al., 2020).

The reasons for the reduced protein intake in this demographic are multifactorial; these are best described in the recent review by Walker-Clarke, Walasek and Meyer (2022). This low protein intake contributes towards the development of sarcopenia: . Sarcopenia significantly increases the risk of falls (Lim & Kong, 2022), frailty (Woo et al., 2015), morbidity and mortality (Sobestiansky et al., 2019). Sarcopenia progression can be reduced through adequate nutrition in combination with exercise (Colonetti et al., 2023; Hernández-Lepe et al., 2023; Kang et al., 2019; Nasimi et al., 2023). Our previous review (Giles et al., 2024) highlighted the positive effect of protein supplementation and fortification on muscle mass. Such a protein supplement, whey protein, has been shown to be a beneficial protein source for fortification due to its high leucine content (Etzel, 2004), bioavailability (Burd et al., 2012; Pennings et al., 2011) and digestive properties (Boirie et al., 1997;

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Mulet-Cabero et al., 2020). These characteristics give whey protein a high digestible indispensable amino acid score (Rutherfurd et al., 2015).

Despite the nutritional benefits of whey protein, it has some sensory attributes with negative associations, limiting its acceptance and consumption. A key driver for disliking of whey protein-based supplements is mouthdrying (Zhang et al., 2020). The mechanism responsible for whey protein-associated mouthdrying is not fully understood; current theories were summarised in the authors' recent review (Giles et al., 2024). In this review, mouthdrying was attributed to a combination of interactions of whey protein with salivary proteins and the oral mucosa. Increased oral friction is a common pathway to these mechanisms, meaning the addition of polysaccharides as lubricants may reduce these interactions. It was proposed this may be a result of lubricants competitively binding to the oral mucosa, binding to whey protein, and/or increasing the rate of oral clearance.

1.2. Justification of selected polysaccharides to increase lubrication

Polysaccharides have been investigated previously for their intrinsic lubrication properties. Xanthan gum (XG) and guar gum (GG), commonly used to modulate viscosity, have contrasting conformations: GG has a random coil conformation whereas XG has a rigid rod conformation. Li et al. (2022) investigated the impact of additional lubrication of WPI using XG, where it was shown that the addition of XG led to a reduction in friction in the lower boundary regimes, due to the brush effect of the polysaccharide interacting with the WPI particle. In agreement with this, when comparing the two in aqueous solutions, Ji et al. (2022) found that XG had higher lubricating capacity at lower sliding speeds, compared with GG, but that this relationship was reversed at higher speeds (<20 mm/s). The mouth experiences a wide range of sliding speeds during oral processing, so it is unclear which of these is likely to correlate with sensory perception. Ji et al. (2023) investigated the use of XG, GG and carboxymethyl cellulose in combination with whey protein in an oil-in-water emulsion: the study reported that the addition of 0.2% XG led to instability and induced oil droplet aggregation, whereas the uncharged GG (added at 0.235%) did not (Ji et al., 2023). GG decreased the friction coefficient of the whey protein-oil emulsion more than XG which the authors attributed to the lower particle size and aggregation levels (Ji et al., 2023). However, the omission of a non-polysaccharide control means these results can only be compared with each other and not with a whey-oil emulsion. The study also omits to include an aqueous suspension of whey, meaning all whey samples are an oil-in-water emulsion, so the effect of polysaccharides on whey protein alone cannot be elucidated. When using a trained sensory panel, a correlation was reported between the degree of shear thinning and creamy, thick and fatty sensations (Ji et al., 2023). However, the study did not report significant differences in mouthdrying or slipperiness perception using an untrained panel (Ji et al., 2023). Previous work in other models has shown that the use of a hydrocolloid thickener led to a reduction in mouthdrying perception (Rossetti et al., 2009), meaning it is unclear if this is an intrinsic property of whey protein or due an investigative limitation.

Whilst previous research has investigated the ability of XG and GG to act as lubricants in isolation (Ji et al., 2023), research into their effect in combination is limited. It was previously shown that when GG and locust bean gum were applied in combination, they produced a different rheological profile than the one shown by either gum alone (Garrec & Norton, 2012). Our review suggested that whey protein-associated mouthdrying is a result of multiple mechanisms (Giles et al., 2024); therefore, using polysaccharides with different properties may address different causes of mouthdrying, leading to a greater reduction of the mouthdrying sensation.

The use of other polysaccharides as lubricants has also been investigated: maltodextrin is a good potential lubricant for whey protein due to its high emulsifying properties and sweet taste (Akhtar & Dickinson, 2007). Increasing sweetness in protein-beverages has been shown to decrease mouthdrying through a cognitive pathway (Methven et al., 2010); thus, maltodextrin has the potential to ameliorate mouthdrying both physically and cognitively. Blok et al. (2020) investigated the sensory impact of the addition of maltodextrin to iced coffees and showed that maltodextrin levels correlated with creaminess and slipperiness perception. This was supported instrumentally, where the friction coefficient reduced upon addition of maltodextrin (Blok et al., 2020). However, older adults have reported excessive sweetness as a common reason for rejection of oral nutritional supplements (Zhang et al., 2020), so this should be added with caution.

1.3. Co-spray drying whey protein with polysaccharides to increase lubrication

Spray drying is part of the commercial production process of whey protein isolate (WPI), but has not been fully utilised in combination with polysaccharides for the modification of WPI's sensory properties. It is hypothesised that the drying process could be optimised to increase lubrication through the inclusion of a second stage of drying of WPI with additional ingredients using a fluidised-bed agglomerate system (co-spray drying). To the authors' knowledge no work exists investigating the effect of co-spray drying WPI with polysaccharides (XG, GG, maltodextrin) on mouthdrying perception; therefore, this methodology may be an unutilised opportunity to modify the mouthfeel of WPI. Previous work has focused on adding polysaccharides to an existing whey protein-fortified product (Ji et al., 2023), rather than using them to coat whey particles before addition into products, with the aim of reducing interactions between whey protein and components of the oral cavity. The previous studies used the addition of high levels of polysaccharides, leading to large changes in viscosity and physical structure, meaning the impact of lubrication alone cannot be elucidated. It is also possible that these levels would impact flavour and consumer acceptance, which has been omitted from some previous work (Li et al., 2022). The authors propose that co-spray drying has the potential to increase lubrication and impact mouthdrying with lower levels of polysaccharides.

Spray-drying may have the capacity to improve taste: encapsulations have been previously shown to reduce the bitterness perception of whey protein hydrolysates (Ma et al. 2014; Yang et al. 2012). These flavour-focused results indicate that this approach could reduce interactions between whey proteins and taste receptors and influence the sensory profile differently to simply mixing the ingredients.

Previous research has investigated the capacity of spray drying to improve solubility: Ji et al. (2017)reported that WPI encapsulated with lecithin had an altered particle size, bulk density, porosity and particle shape. Overall, a high concentration of lecithin, leads to a more rapid influx of water and improved solubility of WPI (Ji et al., 2017). Whilst this study did not look at the sensory impacts of encapsulation, it supports its use as a potential mitigation strategy for mouthdrying by reducing interactions between whey proteins and the oral mucosa and saliva. No studies to the authors knowledge have investigated the effect of this technique on mouthfeel properties, leading to the need for further investigation.

1.4. Research hypothesis

Although previous work has investigated mixing WPI with polysaccharides or co-spray drying of whey protein with other materials, to the authors knowledge, studies have not used co-spray drying of WPI and polysaccharides to investigate the impact on lubrication and mouthfeel. This study bridges the gap between the ability of co-spray drying to increase lubrication and the subsequent impact on sensory perception. It is also noted that in the literature, researchers use high levels of polysaccharides, leading to large changes in the viscosity of the product and the subsequent nutritional content of WPI as an ingredient. This study, using low levels of polysaccharides to maintain the high

protein content (>90%) of WPI, hypothesises that co-spray drying WPI with maltodextrin, XG and/or GG would significantly decrease instrumental friction. It was unknown which polysaccharide would provide the best tribological profile but based on the findings of Ji et al. (2023) it was predicted that the ideal candidate would also display a minimal change in particle size distribution and viscosity, representing low levels of aggregation. We hypothesise that the decrease in instrumental friction will be partnered with a reduction in mouthdrying perception by a trained sensory panel.

2. Methodology

2.1. Materials

Whey protein isolate (WPI) was provided by Volac Whey Nutrition Ltd (Hertfordshire, UK). This contains 92% protein (calculated by nitrogen content) and is instantized with a sunflower lecithin inclusion (E322). Maltodextrin, XG and GG were sourced from Special Ingredients (Chesterfield, UK).

2.2. Powder preparation

Coated samples were prepared with a fluidised bed spray dryer using 5 kg batch agglomeration and microencapsulation (LZL Engineering, Owatonna, US): 3 kg of WPI powder was fluidised and heated to 35 °C. When at temperature, the WPI powder was sprayed with water from a top-nozzle spray for 7 min before replacing this feed with polysaccharides dissolved in warm water to allow for optimum substance coating (see Table 1). XG and GG were prepared as solutions in 500 mL of warm water; the amounts used were the upper limit of solubility whilst mixing with a magnetic stirrer (ThermoFisher, UK; setting 3), corresponding to 0.3 and 0.5% w/v respectively. The level of maltodextrin used (4.76% w/v) was based on both initial sensory tastings (data not shown) to ensure no perceptible increase in sweetness and to ensure the thickness of the suspension was suitable for top-nozzle spray drying. The speed of spraying was manually manipulated (15–40 rpm) to control humidity inside the bed. During spraying, the inlet and outlet temperature ranged from 50 °C–67 °C and 25 °C–36 °C respectively. After addition of ingredients, the powder was dried to 45 °C to achieve the desired moisture content in the final powder of 5% w/w (±1%), and then immediately cooled to 35 °C before collection. Powders were stored in airtight containers at room temperature (19 ± 2 °C) until required and used within 8 months.

2.3. Powder analysis

2.3.1. Particle size

Particle size of dry powders was measured using a Malvern Mastersizer 3000 (Malvern Instruments, UK) with Aero S attachment, connected to a DustControl DC 1800 Eco vacuum.

2.3.2. Scanning electron microscopy (SEM) and digital microscopy

SEM was performed at 5–20 kV using the four quadrant back scatter electron detector on a SEM Stereoscan 360 (Cambridge Instruments). Samples were mounted onto small SEM aluminium stubs via sticky conducting carbon tabs and the sample excess removed through tapping. Samples were then sputter coated with a thin layer of gold, using an Edwards S150B Sputter Coater, prior to examination in the SEM. Images were taken in 4 areas of the sample stub at a range of magnifications: images chosen were representative of the larger pool of images selected.

Microscopy images of co-spray dried powders were collected using a VHX7000N series microscope (Keyence, Milton Keynes, UK) with a VHX control system (version 21.02.24.0 A (1.1.8)0.01.00.00.04). 1 g of powder was added to the microscope slide immediately prior to imaging. No stains, fixers or contrast enhancers were used due to the intrinsic fluorescence of WPI; this has been described previously as a result of the high tyrosine content of whey protein (Zhang et al., 2014). Ring lighting was used throughout. All images collected were 2880 × 2160 pixels. Three images were taken of each sample using different areas of the slide to ensure evaluated images were representative. Images were analysed using PowerPoint (Version 2403 Build 16.0.17425.20176) to add circles around particles corresponding to average particle size. Unedited images are included in Appendix A.

2.4. Suspension preparation

To prepare 10% w/v suspensions, 25 g (±0.5 g) powder was made up to 250 mL using bottled water (Harrogate Spring Water, Harrogate, North Yorkshire, UK) and stirred using a magnetic stirrer for 60 min at room temperature (19 ± 2 °C), resulting in a final concentration detailed in Table 2. Samples were refrigerated overnight (16–20 h) prior to use and analysed within 24 h of production.

2.5. Suspension analysis

2.5.1. Particle size

Particle size of suspensions was completed using the Hydro EV attachment to the Malvern Mastersizer, in order to mirror the measurements made on the powders (section 2.3.1). Measurements were taken in triplicate using the Mastersizer software (version 3.81).

2.5.2. Zeta potential

Suspensions were diluted 100 times in water (HPLC grade water) for zeta-potential measurements, which were performed using Nano-S Zetasizer (Malvern Instruments, UK) at 30 °C with an equilibration time of 120 s. Samples were prepared in triplicate on three separate days, leading to nine values being obtained for each sample.

2.5.3. Rheological profile of suspensions

Rheological properties of WPI samples were analysed using an oscillatory rheometer (MCR 302, Anton Paar, St. Albans, UK) fitted with a 40 mm diameter smooth rotating plate adjusted to 25 °C. Work was completed in a temperature-controlled room (19 ± 1 °C) with samples acclimatised to room temperature for 1 h prior to recording. After loading the sample onto the lower plate surface, a rest time of 5 min prior to measurement was established for sample relaxation and temperature equilibration. Amplitude sweeps of the samples were obtained

Table 1
Respective w/w percentages of maltodextrin (M), xanthan gum (XG) and/or guar gum (GG) co-spray dried with whey protein isolate (WPI).

Powder (p)	Maltodextrin (%)	Xanthan gum (%)	Guar gum (%)
p (WPI/M)	4.76	–	–
p (WPI/XG)	–	0.3	–
p (WPI/GG)	–	–	0.5
p (WPI/M/XG)	4.76	–	0.5
p (WPI/M/GG)	4.76	0.3	–
p (WPI/M/XG/GG)	4.76	0.15	0.15

Table 2
Respective levels of whey protein isolate (WPI), maltodextrin (M), xanthan gum (XG) and/or guar gum (GG) that were included in final 10% w/v suspensions.

Suspension	Whey protein isolate (%)	Maltodextrin (%)	Xanthan gum (%)	Guar gum (%)
WPI	10	–	–	–
WPI/M	9.52	0.48	–	–
WPI/XG	9.97	–	0.03	–
WPI/GG	9.95	–	–	0.05
WPI/M/GG	9.47	0.48	–	0.05
WPI/M/XG	9.49	0.48	0.03	–
WPI/M/XG/GG	9.49	0.48	0.015	0.015

by applying an oscillation at a frequency of 1 Hz for strain values ranging from 0.01 to 10 % in 12 steps. A strain of 10% was then chosen in the linear viscoelastic region for frequency sweeps, where frequency was varied from 100 to 0.01 Hz. Viscosity was recorded through measurements from shear rates of 0.001–1000 s^{-1} in 42 logarithmic steps. Two analytical repeats were taken at each recording session and samples were prepared on three separate days, leading to six values being obtained for each suspension.

2.5.4. Tribological profile of suspensions

Tribological measurements were performed with the oscillatory rheometer (MCR 302, Anton Paar, St. Albans, UK) equipped with a tribology cell attachment (T-PTD200, BC12.7, Anton Paar, St Albans, UK). A ball-on-three-pin tribo-pair with a glass probe and three polydimethylsiloxane (PDMS) pins (6 mm pin height), inclined at 45° to the base, was used. Analysis was completed in a temperature-controlled room (19 ± 1 °C) with samples acclimatised to room temperature for 1 h prior to recording. Temperature was controlled at 25 °C and a normal force of 1 N was applied. To measure the friction coefficient, samples were added to the tribology cup to the level of the top of the pins and the friction coefficient was measured as a function of sliding speed. Sliding speed between 1E-05 m/s and 1 m/s was used as the measurement window. One measurement consisted of three runs using the same pins, after which the pins were replaced. The data from the first run was disregarded as the results deviated from the data in the other runs: this is likely to be an instrumental measurement error as a result of friction against the new pin surfaces or an opposition to flow based on material loading into the cell. This is commonly observed when carrying out these measurements. The data from the second run was selected for further analysis, where four regimes were seen: the profiles from an example data set detailing these regimes is available in Appendix B. Each sample was prepared in triplicate and the average of the three datasets used for analysis.

2.5.5. Sensory profiling of suspensions

A screened and trained sensory panel (n = 10; females 9, male 1) were used in this study, based at the MMR Sensory Science Centre in the UK (MMR Research Worldwide Ltd, Wokingham, UK). The panel training for this study and data collection sessions were run by the University researchers. The panel were given further training on mouthfeel attributes used for WPI profiling (minimum 3 h). Sensory evaluation was carried out in a temperature-controlled room (23 ± 2 °C) in isolated booths. A consensus vocabulary was developed by the panel during training and using reference standards (26 attributes; 2 appearance, 4 aroma, 8 taste and flavour, 5 mouthfeel, 7 aftereffects); the finalised vocabulary and references are detailed in Appendix C. WPI samples were evaluated in duplicate according to a balanced design using unstructured line scales (scaled 0–100) with appropriate anchors. Panellists were able to see previous scores within the same tasting session. After-effects were scored after a 30 s delay. Samples were presented monadically in transparent cups (30 mL). Low salt crackers (Carr's water crackers, McVities, UK) and warm filtered tap water were provided as palate cleansers between samples during an enforced break (2 min). Evaluation was carried out under artificial daylight. Sensory questions were presented, and data collected, on Compusense (cloud version, Ontario, Canada).

2.6. Statistical analysis

All instrumental data was analysed using Excel (version 2312) and XLSTAT (version 2021.5.1). Values for particle size (powder) and zeta potential (suspension) were analysed using one-way ANOVA and post-hoc Tukey tests with significance offset at $p < 0.05$. For rheology of suspensions, the viscosity values at 51.8 s^{-1} were used for this ANOVA and Tukey analysis. The friction coefficients and sliding speeds from tribology were analysed likewise. Sensory questions were analysed using Senpaq (Kent, UK). Two-way ANOVA was used where the sample was the fixed effect and the panellists the random effects, with both effects tested against the sample by panellist interaction. Tukey HSD tests were used for multiple pairwise comparisons to assess significance between samples, at a significance value of $p < 0.05$. Correlation coefficients between average instrumental friction (tribology) and sensory perception of mouthfeel attributes was determined using the CORREL function of Excel (version 2312). Sensory perception for mouthdrying was then compared at the highest points of correlation using the same statistical methods as previously performed for sensorial analysis.

3. Results & discussion

3.1. Particle size of powders and suspensions

It was anticipated that co-spray drying WPI with polysaccharides would increase particle size as the ingredients would coat the external surface and create a partial encapsulation. In addition, previous research reported an increase in particle size upon addition of polysaccharides to oil-whey emulsions due to increased agglomeration (Ji et al., 2024). When comparing the mean particle size of powders, the addition of GG or XG led to an increase in particle size: p (WPI/GG), p (WPI/XG), p (WPI/M/GG) and p (WPI/M/XG) had a significantly larger mean particle size than WPI ($p < 0.0001$). Full results from the pairwise comparisons of mean particle sizes are included in Appendix D. This is also represented by the particle size distribution curves, where a shift towards larger particles is demonstrated upon inclusion of XG or GG (Fig. 1A). It was predicted that this would also be seen when coating with maltodextrin; however, there was no significant difference in particle size for p (WPI/M) compared with WPI ($p = 0.115$).

A higher particle size of dry powders has previously been linked to improvements in porosity, solubility (Onwulata et al., 2004), and wettability (Ji et al., 2017). The sample p (WPI/GG), with the greatest mean particle size, was observed to have improved solubility compared to WPI during the preparation of suspensions; this is in agreement with the literature, although measurement of solubility was outside the scope of the current study. This is important both in manufacturing contexts, to ensure even incorporation of additional ingredients, and for consumer acceptance, in enabling consumers to make smooth fortified beverages at home quickly.

When comparing the mean particle size of suspensions, no significant difference was observed between WPI and WPI/M ($p = 1.000$). All samples experienced a similar level of heating during the co-spray drying process, so this omission of a difference indicates that the WPI molecules did not unfold or significantly change the degree of aggregation as a result of this methodology (Li et al., 2022). All other suspensions showed an increase in average particle size compared with WPI: WPI/M/XG and WPI/M/XG/GG were significantly larger than WPI ($p = 0.030$ and $p = 0.006$ respectively). This increase was greatest for suspensions containing XG, compared with those containing GG, which was in direct contrast to the particle size data collected on dry powders. It is likely that particle size of suspensions containing XG increased with the addition of water due to increased agglomeration, leading to clumping within the suspension. This was visually observed during preparation where samples containing XG took longer to dissolve. The addition of XG has been previously linked to agglomeration (Ji et al., 2023). It is unclear how the contrasting charge and conformation of XG and GG may impact overall particle agglomeration, dissolution and distribution in suspensions, and the subsequent impact of this on sensory perception of beverages.

3.2. Microscopy of powders

Microscopy was used to visualise the external surface of the particles and determine whether the co-spray drying of WPI with polysaccharides led to a change in particle structure and coating of the WPI's surface.

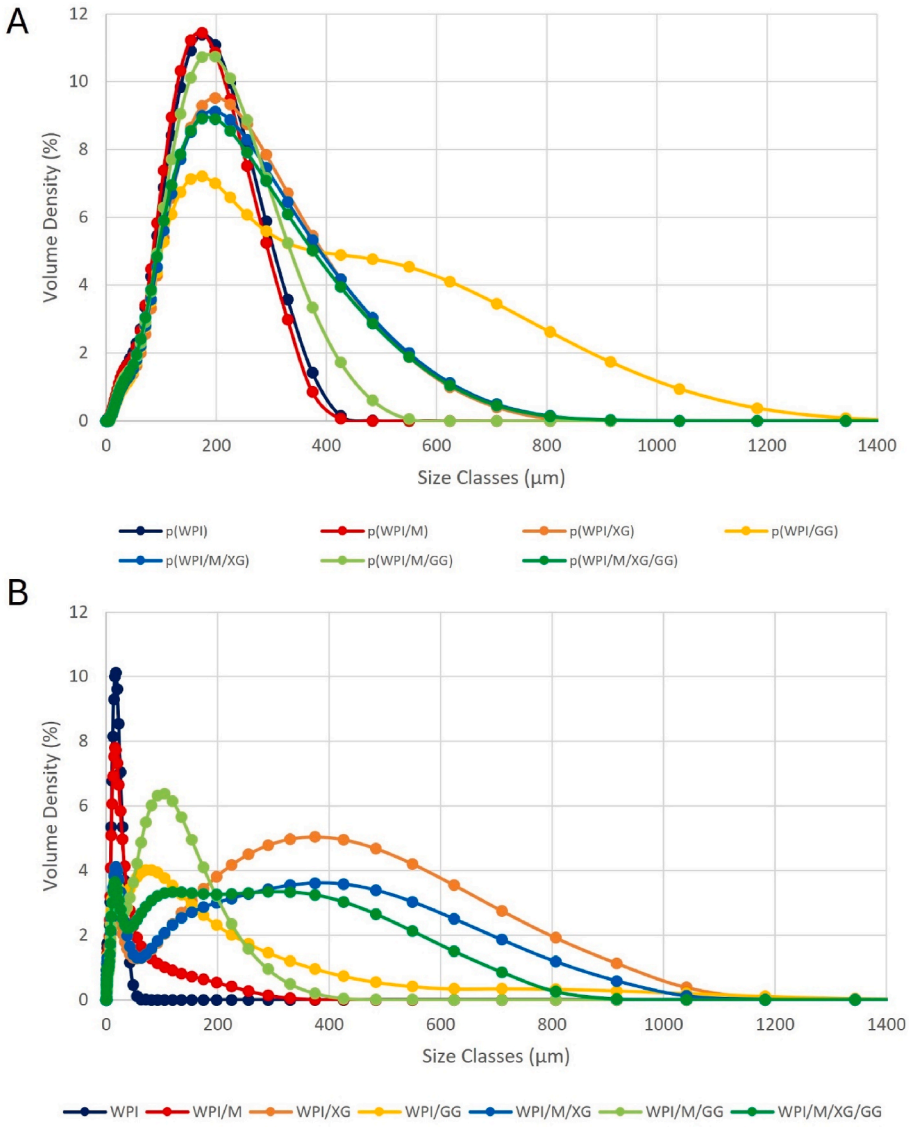

Fig. 1. Average particle size distribution curves from triplicate samples for whey protein isolate (WPI) co-spray dried with 4.76% maltodextrin (M), 0.3% xanthan gum (XG), and/or 0.5% guar gum (GG) in isolation and in combination (0.15% XG and GG in WPI/M/XG/GG); [A]: dry powders; [B]: 10% w/v suspensions.

When looking at the external surface of WPI (Fig. 2A), it can be seen that this typically has a spherical shape, circled in blue, with some smaller particles binding on the external surface. These have been indicated with a purple circle (Fig. 2A): they have a particle size of ~100 μm, the average particle size of lecithin (Cabezas, Madoery, Diehl, & Tomás, 2012, pp. 39–50). Thus, it is anticipated that this is lecithin on the external surface of WPI: these samples have been pre-treated with lecithin to increase wettability as is standard practice in the industry, this ensures the work has industrial relevance and enables comparison with a commercially-available product. Previous research showed that coating WPI with 0.5%, 2% or 5% lecithin increased wettability by increasing the rate of water penetration (Ji et al., 2017).

The addition of maltodextrin during spray drying (Fig. 2B), had a minimal impact on appearance of the WPI particle: it still has a spherical shape and smooth external surface, circled in blue. In this sample there is still a high proportion of the WPI particle surface accessible, suggesting that this would still be able to interact with the oral mucosa and salivary proteins. Some particles, circled in red, are seen with a particle size of ~120 μm: it is possible that these are maltodextrin particles, suggesting that some of the maltodextrin may not have combined with WPI and may be present in the powder in an isolated form. Due to the similar particle size between maltodextrin and lecithin, it is not possible to conclude which of these are likely to be the particles observed in the images: however, the difference between Fig. 2A and B suggests that the maltodextrin has had a negligible coating effect.

When WPI was co-spray dried with GG, the proportion of particles on the external surface of WPI greatly increased (Fig. 2D) compared with the addition of maltodextrin (Fig. 2B). Here, the typical smooth spherical shape was observed with less frequency due to the high number of particles on the external surface of WPI. GG had an average particle size of 56 μm (Appendix E), which matches to the size of the spheres shown with yellow circles (Fig. 2D), further supporting that this is likely to be GG binding on the external surface of WPI via electrostatic and hydrophobic interactions. Whilst the WPI coverage increased, in some areas the WPI particle was still visible (Fig. 2D), suggesting a partial encapsulation had taken place. Similar encapsulation levels are seen when co-spraying WPI with XG (Fig. 2C). The smaller particles, shown with orange circles (Fig. 2C), match the average particle size of XG, 30 μm (Appendix E), supporting the hypothesis that co-spray drying leads to the placement of polysaccharides on the external surface of WPI and a partial encapsulation. Again, the original smooth WPI surface can still be seen in places, as evidenced with the blue circle (Fig. 2D). XG (Srikaeo

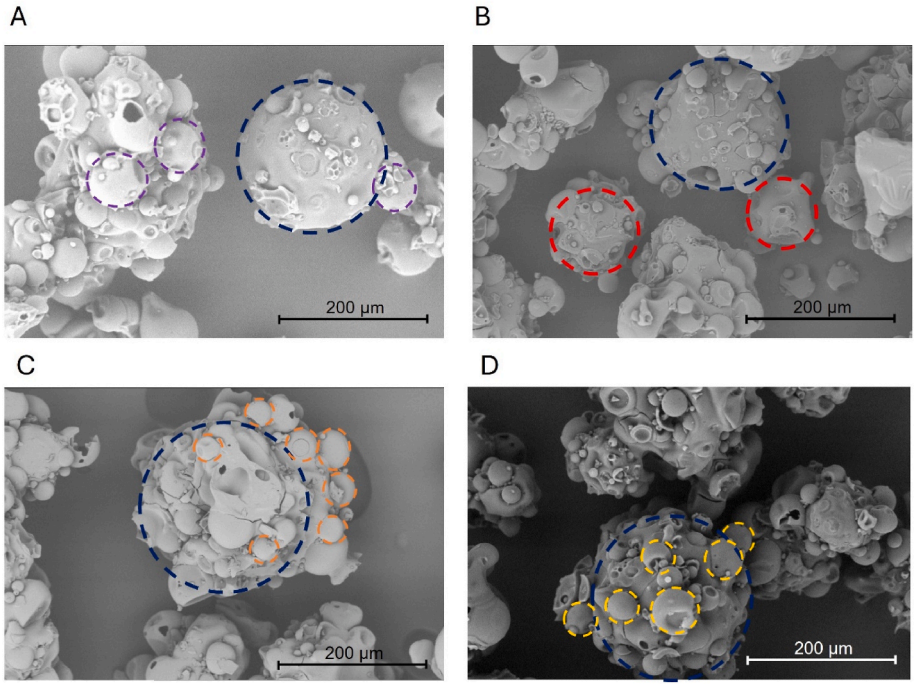

Fig. 2. SEM of powders at 200× magnification; [A]: whey protein isolate (WPI) powder in isolation; [B]: WPI co-spray dried with 4.76% maltodextrin; [C]: WPI co-spray dried with 0.3% xanthan gum; [D]: WPI co-spray dried with 0.5% guar gum. Blue circles have been used to show the WPI particles. Purple circles have been used to indicate suspected lecithin particles, yellow circles for guar gum, and orange circles for xanthan gum. Images without these circles have been included in Appendix A.

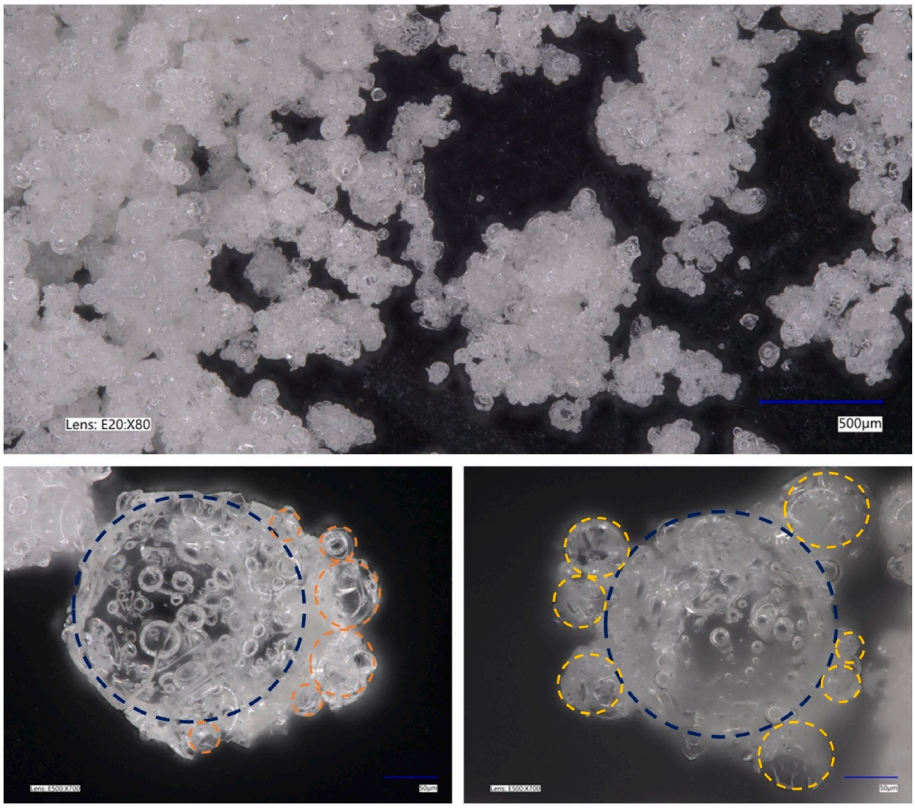

Fig. 3. Digital microscopy; [A]: whey protein isolate powder in isolation, scale bar represents 500 μm; [B]: whey protein isolate (blue) co-spray dried with 0.3% xanthan gum (orange), scale bar represents 50 μm; [C]: whey protein isolate (blue) co-spray dried with 0.5% guar gum (yellow), scale bar represents 50 μm. Circles added manually representing average particle size.

et al., 2018) and GG (Barber et al., 2023) are both largely indigestible, so this partial coating rather than complete encapsulation might be advantageous for bioavailability by ensuring the whey protein was still accessible for digestion (bioavailable), whilst reducing the possible points of interaction between WPI and the oral mucosa or salivary proteins. This balance is promising for improving sensory properties without reducing bioavailability and digestibility.

These images were further supported by digital microscopy: here, WPI in its powdered form was shown to be a spherical particle which clusters together when spray dried (Fig. 3A). Upon addition of XG (Fig. 3B), some external coating was observed: the particle size of the larger sphere, circled in blue (Fig. 3B), matches the size expected for WPI. Similarly, the particle size of the smaller spheres (35 μm), circled in orange (Fig. 3B), attached to the right side of the sphere matches the average particle size recorded for XG (30 μm). This is detailed in Appendix E. Therefore, it is highly likely that XG is on the external surface of the WPI. For powders containing GG, it can be seen that particles with an estimated diameter of ~50 μm, circled in yellow, are bound to the external surface of a suspected-WPI particle (Fig. 3C). GG had a mean particle size of 60 μm (Appendix E), so this is likely to be GG on the external surface of a WPI particle. Echoing the conclusions of SEM microscopy, GG appears to have formed a partial coating rather than a full encapsulation (Fig. 3C) which may improve the sensory profile without impacting bioavailability.

3.3. Zeta potential and pH of suspensions

The mean zeta potential for the suspensions ranged from −21.4 to −25.8 mV (Appendix F), and such high absolute charges are considered to have sufficient electrostatic repulsion to inhibit agglomeration and settling, giving suspension stability (Hanaor et al., 2012). The inclusion of polysaccharides did not significantly effect the zeta potential, and hence was unlikely to substantially effect stability. There is limited evidence for a link between zeta potential and sensory perception; Carter and Drake (2021) proposed a correlation between zeta potential and astringency perception, with a charge closer to zero being associated with reduced astringency due to a decreased tendency of the particles to interact with salivary proteins. This relationship has not been repeated in other work so should be interpreted with caution. Particles with greater charge have been linked to increased particle size through increased agglomeration (Carter and Drake, 2021): however, our suspensions demonstrated significant changes to particle size, without an observed change in zeta potential. Therefore, it is unknown which of these will impact sensory perception.

The pH of the suspensions approximated neutrality (Appendix F) and was not significantly influenced by the addition of the polysaccharides. Previously, oil-in-water emulsions stabilised by whey aggregates were negatively charged at pH 7 (denoting repulsion) but positively charged at pH 3.3 which would lead to attractive interactions (Ji et al., 2024). More acidic WPI suspensions are commonly described as more mouth-drying (Withers et al., 2013) and this may represent a reduction in stability and an increase in interaction both between particles (agglomeration), or with salivary proteins and components of the oral mucosa.

3.4. Rheological profiles of suspensions

When analysing the viscosity of suspensions at different shear rates, shear thinning was observed in all suspensions at shear rates below 100 s^{-1} (Fig. 3); this is consistent with the literature (Tang et al., 1993). When comparing the effect of polysaccharides, shear thinning was most pronounced in suspensions containing XG (WPI/XG and WPI/M/XG) where the gradient of the line was the steepest (Fig. 3). Ji et al. (2023) also recorded increased shear thinning in suspensions containing XG and suggested that enhanced reorganisation of the XG particles led to increased order and reduced resistance. Shear thinning with XG was reported by Ji et al. (2022) as the breakdown of large aggregated particles into smaller particles, leading to a decrease in viscosity. Thickness perception is influenced by shear thinning behaviour and viscosity (Koliandris et al., 2010). Ji et al. (2023) reported that WPI-oil emulsions with greater shear-thinning behaviours were related to a reduced thickness perception. It was also suggested that higher levels of shear thinning may facilitate increased ease of swallowing and reduce organoleptic viscosity perception (Vieira et al., 2020).

Across all tested shear rates, the addition of maltodextrin had no observed effect on viscosity (Fig. 4). The levels of maltodextrin added in this study were low (0.48% w/v) to avoid displacing the high protein content of WPI beverages and excessive sweetness, a common reason for disliking of oral nutritional supplements by older adults. Ji et al. (2023) highlighted the importance of molecular weight on the ability of maltodextrin to impact viscosity and lubrication: it is possible that this explains the differing effect of maltodextrin on viscosity between our study and Vieira et al. (2020), who reported a significant increase in viscosity by adding 0.75% maltodextrin to milk.

Contrastingly, the addition of either gum led to an increase in viscosity. This aligns with expectations as gums create networks of entanglements with water increasing resistance (Saha & Bhattacharya, 2010). At lower shear rates WPI/XG (0.03 %w/v) was associated with an increased viscosity compared with WPI/GG (0.05% w/v): this aligns with particle size data and supports the suggestion that XG increased agglomeration. This trend was conserved across shear rates, however the difference between samples reduced at higher shear rates. It echoes the findings of Ji et al. (2023) who reported higher viscosity in whey protein-oil emulsions containing 0.2% XG compared with 0.235% GG at shear rates below ~50 s^{-1}, but at higher shear rates GG was associated with an increased viscosity. Whilst, in our study XG remains the most viscous up to ~500 s^{-1}, it is suggestive of the same trend that at lower shear rates XG has the greatest effect on viscosity of WPI, but with higher shear rates the difference reduces. It is possible that the lower levels of XG and GG in our study (0.03% and 0.05% respectively) can explain the differing results with Ji et al. (2023). The levels chosen were the upper limit of solubility when mixing with a magnetic stirrer to facilitate top-nozzle spray drying. Additionally, the intention was to use low levels to minimise protein displacement.

As seen in our study, it is common practice during descriptive rheology to record viscosity over a large range of shear rates, to reflect the range experienced during oral processing. To facilitate quantifiable comparisons, viscosity is measured at 50 s^{-1}: this speed is considered to be representative of shear rates experienced during swallowing and thickness perception (Wood, 1968; Chojnicka et al., 2008; Chojnicka-Paszun et al., 2014). Our studies have compared viscosity at 51.8 s^{-1} as this is the closest value recorded by the instrument; this was reported previously (Moret-Tatay et al., 2015). When comparing the effect of polysaccharide coatings on viscosity at 51.8 s^{-1} (Fig. 4), samples containing XG presented the highest viscosity (WPI/XG > WPI/M/XG > WPI/M/XG/GG). The increase in viscosity of WPI/XG compared with WPI was significant ($p < 0.0001$). However, the link between viscosity and sensory perception for whey beverages is not fully characterised; a poor correlation between viscosity and sensory perception was previously reported (Ji et al., 2023). Whilst the addition of GG also increased the viscosity compared with WPI, the effect was smaller than for XG.

Shear thickening behaviour was seen at shear rates in excess of 100 s^{-1} for all suspensions (Fig. 4). This was previously attributed to particle clustering, leading to an increased resistance to flow (Sağlam, Venema, de Vries, Shi, & van der Linden, 2013). An alternative explanation can be found in the instrumental limitations of rheology: changes at higher shear rates may be reflective of secondary flow effects due to turbulent flow conditions (Ewoldt, Johnston, & Caretta, 2015). The authors reported that for these viscosity measurements only values corresponding to shear rates ranging 10-200 s^{-1} are likely to be true recordings (Ewoldt et al., 2015). Therefore, the shear thickening seen in Fig. 4 can be disregarded as a mechanical measurement, and as such will not be

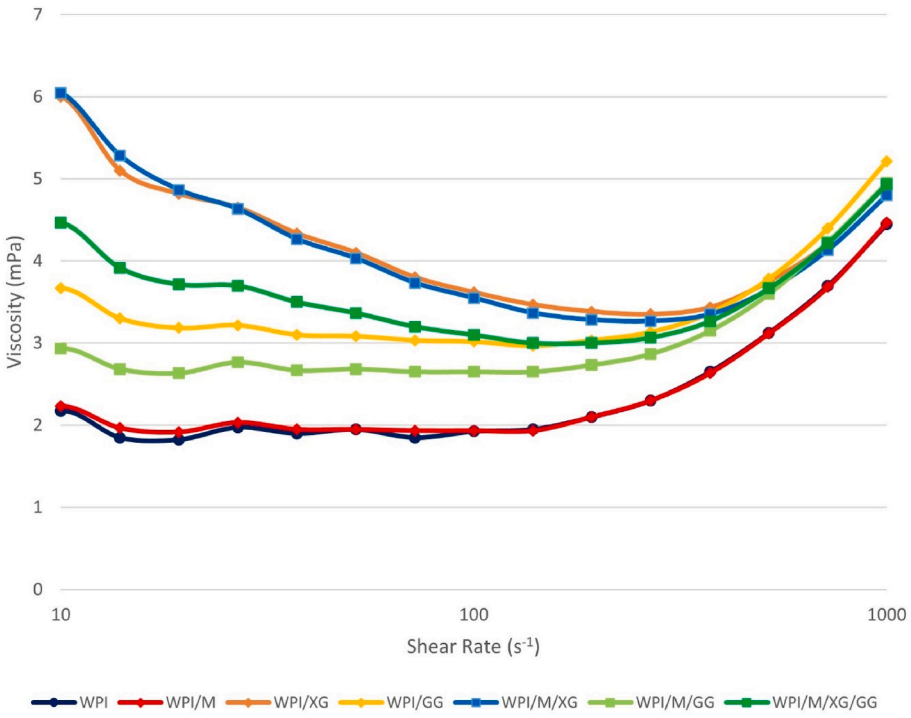

Fig. 4. Exploration of the effect of co-spray drying whey protein isolate (WPI) with 0.48% maltodextrin (M), 0.03% xanthan gum (XG), and/or 0.05% guar gum (GG) in isolation and in combination (0.015% XG and GG in WPI/M/XG/GG) on the viscosity (mPa/s) of 10% suspensions over varying shear rates (10-1000 s^{-1}).

discussed.

3.5. Tribological profiles of suspensions

Owing to the large range of deformations occurring in the mouth, a single rheological parameter cannot fully explain the large range of mouthfeel perceptions experienced (Theocharidou et al., 2021; Krzeminski et al., 2012; He et al., 2016). However, the combination of rheological results with tribological profiles can be used to more accurately portray the experience of oral processing. The instrumental friction coefficient has been shown to correlate well with sensory perception (Chen & Stokes, 2012). Frictional curves given as a function of sliding speed typically display four regimes based on the shape of each curve (Appendix B): these have been previously documented as the stick-and-slip effect (Li et al., 2022). In the current study, the speed ranges identifying these regimes were consistent across suspensions (Fig. 5), indicating that whilst the specific structure influenced the friction coefficient, the fundamental lubrication behaviour was comparable. This contrasts findings from whey-polysaccharide-oil emulsions reported by Ji et al. (2023), where changes in sliding speeds were associated with different regimes between different polysaccharides. This may reflect the higher viscosity of emulsions used by Ji et al. (2023), leading to greater tribological changes.

As noted in the methods, results from the second instrumental run were analysed. When comparing results for this run (Fig. 5A), the addition of either XG (WPI/XG and WPI/M/XG) or GG (WPI/GG) reduced instrumental friction compared with WPI and WPI/M at the lower sliding velocities of regimes 1 and 2. One explanation, given in a previous study reporting a similar decrease in friction in the initial regimes, is that the gums adhered on the protein particles could form hydrated layers in water and achieve hydration and lubrication, preventing the increase in oral friction at low sliding speeds (Li et al., 2022). However, in regime 3 there was a considerable overlap between the samples; in this regime WPI/M and WPI/M/GG displayed the most friction. By regime 4, WPI/GG was the only suspension with a lower friction coefficient than WPI. A possible explanation for the reduction in instrumental friction in WPI/GG compared with WPI was provided by Ji et al. (2023): dispersions with smaller molecules have the ability to limit contact between surfaces, leading to additional lubrication. The authors also suggest that GG is a flexible polysaccharide that easily gets entrained in the measurement gap, wheras XG is a more rigid polysaccharide which has difficulty entering the gap (Ji et al., 2023). This highlights the importance of the conformation of the suspension in its behaviour within the measurement gap. Supporting this is the observation, that WPI/M/XG/GG contained less GG than WPI/GG, and reduced the friction less than the WPI/GG sample. This suggests that the increased flexibility of GG leads to an enhanced lubricating capacity, that is not achieved by XG or maltodextrin.

As viscosity may influence friction, this was accounted for by presenting friction for shear rates multiplied by the viscosity at 1000 s^{-1} (Fig. 4B), a practice previously discussed by Kew et al. (2021). The value of correcting for viscosity is debatable as the magnitude of the impact of viscosity on tribological profile of whey protein is not known. This has previously been calculated for corn syrup solutions (Gamonpilas et al., 2022), but it is anticipated to vary based on the sample type, meaning it is possible that this adjustment may over- or under-estimate the effect of viscosity on friction. However, it has been included to enable comparisons of relative lubrication between suspensions with different viscosities. When corrected for viscosity, the reduction in friction of WPI/GG was still seen, suggesting that this reduction in friction could not be explained by viscosity alterations alone, and is likely to be the result of microstructural differences between suspensions.

Interestingly, the reduction in friction coefficient in WPI/GG was not seen in WPI/M/GG. It is possible that the addition of maltodextrin and the increased complexity of the sample may have prevented the movement of the flexible polysaccharides, leading to difficulty in entering the measurement gap and higher recorded friction. WPI/GG had a lower particle size than WPI/M/GG: this may have resulted from reduced aggregation, which subsequently improved the flow capabilities of this suspension. However, previous literature is unclear on the impact of particle size on ball bearing lubrication with one article claiming enhanced lubrication with smaller particle sizes of milk protein

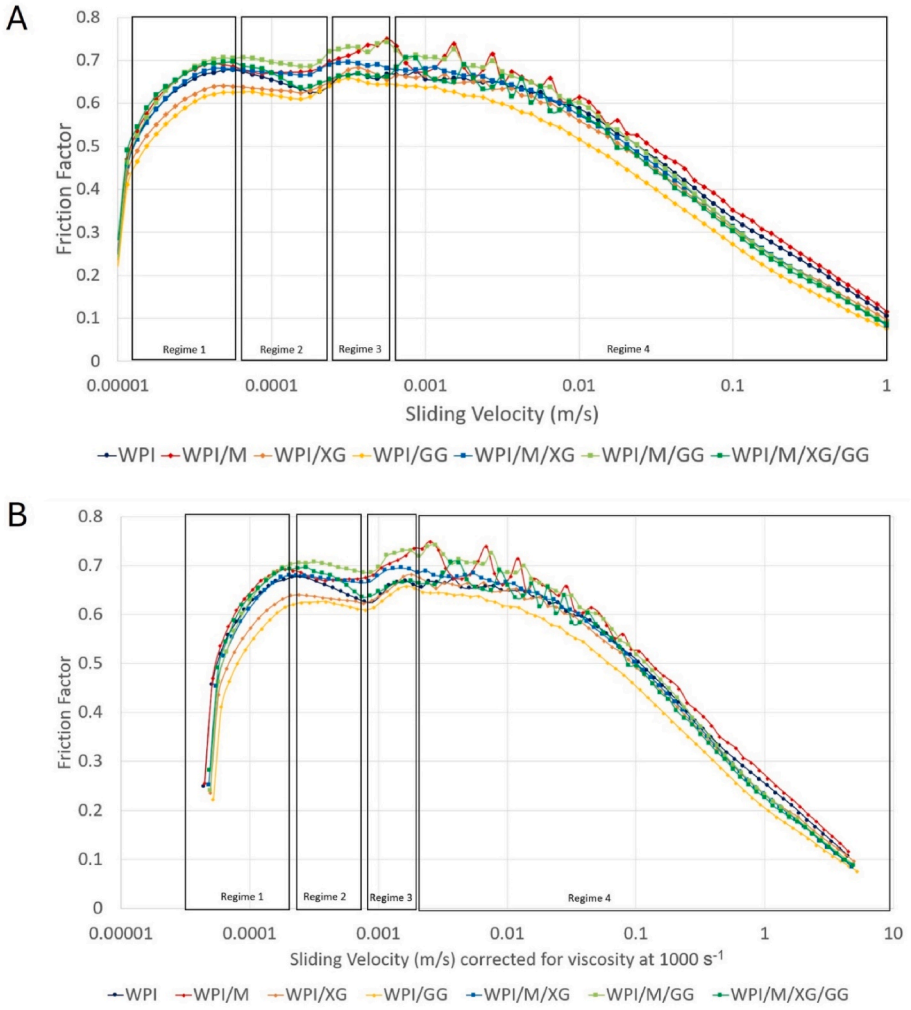

Fig. 5. Lubrication curves of 10% whey protein isolate (WPI) suspensions co-spray dried with 0.48% maltodextrin (M), 0.03% xanthan gum (XG), and/or 0.05% guar gum (GG) in isolation and in combination (0.015% XG and GG in WPI/M/XG/GG). Created using data collected on the second instrumental run; [A]: as a function of sliding speed; [B]: as a function of the frictional parameter (speed * viscosity at 1000 s^{-1}).

solutions (Zhu et al., 2019) and others better lubrication of WPI-oil emulsions with larger particles (Ji et al., 2023). This is echoed in the higher friction measurements of WPI/M/XG/GG where the combination of different polysaccharides appears to have led to increased entanglement within the suspension and more difficulty entering the measurement gap. It was anticipated that the use of polysaccharides as lubricants would have a synergistic or additive effect, but this shows that the final microstructure of samples was more important than the properties of the individual components in determining friction. As such, the combination of a rigid and flexible polysaccharide has had a negative effect on lubrication in this context (Fig. 5). This conclusion was similarly reported by Ji et al. (2023) who stated that the interactions between components and the level of micro-phase separation was responsible for the final properties, rather than the properties of each component. This may explain the different tribological profiles between suspensions containing XG and GG; suspensions with XG had a greater particle size than those containing GG. However, the relationship between particle size and lubrication is debated, with some authors claiming stability, hydrophobicity, and rheological profiles to be more important (Sun et al., 2023) whilst others look predominantly at the effect of molecular weight on friction (Ji et al., 2022). More research is needed to understand the relationship between particle size, microstructure and tribology for whey protein-polysaccharide systems.

3.6. *Descriptive sensory profiling*

Descriptive sensory profiling was completed to understand whether the partial coating of whey provided by polysacchardies sufficiently increased lubrication to cause a change in sensory perception. The panel developed a consensus vocabulary of 26 attributes upon which to evaluate the suspensions: two appearance, four aroma, eight taste and flavour, five mouthfeel and seven after-effects (the references used are detailed in Appendix C and the mean scores in Appendix G). Considering aroma, taste and flavour, there were signficant differences between samples for powdered milk aroma and mushroom flavour ($p < 0.05$). However, the discussion will focus on mouthfeel as this was hypothesised to be signficantly impacted by the addition of polysaccharides. There were significant differences in the perception of mouthcoating and smoothness between the samples (Fig. 6): mouthcoating and smoothness perception were both significantly higher in WPI/GG ($p = 0.0345$, $p = 0.0346$ respectively) and WPI/M/GG ($p = 0.0347$, $p = 0.0126$ respectively), compared with WPI. There were no significant differences between samples for the other mouthfeel attributes investigated such as body, mouthdrying, and slipperiness.

Mouthcoating perception was significantly correlated with perception of body ($r = 0.786$, $p = 0.036$), although the mean differences in body between samples were not significant. Such positive correlations between perceived thickness and mouthcoating have been previously

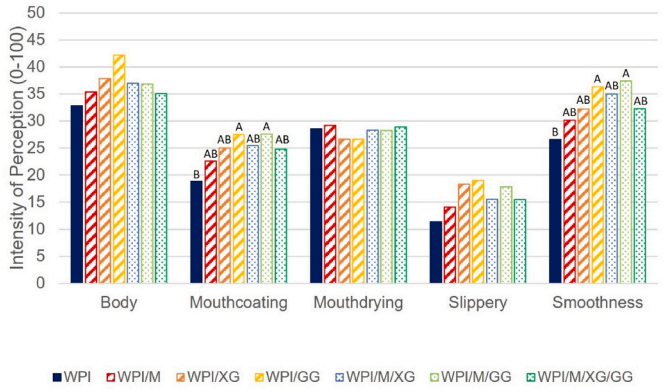

Fig. 6. Mean scores for mouthfeel perception of 10% whey protein isolate (WPI) suspensions co-spray dried with 0.48% maltodextrin (M), 0.03% xanthan gum (XG), and/or 0.05% guar gum (GG) in isolation and in combination (0.015% XG and GG in WPI/M/XG/GG). Samples were scored by a trained sensory panel. Significant differences found for mouthcoating ($p = 0.03$) and smoothness ($p = 0.01$) perception: these were investigated using Tukey to perform multiple pair-wise comparisons ($p < 0.05$).

reported with milk desserts (Ares et al., 2010). This indicates that the addition of GG influenced how the suspension moved within the oral cavity, impacting the sensory experience.

It was suggested earlier that tribological profiles have better correlations with sensory perception than other instrumental recordings (Chen & Stokes, 2012). To investigate this link, correlation coefficients were determined between average friction coefficients and sensory perception of mouthfeel attributes (body, mouthcoating, mouthdrying, slippery and smoothness) using Pearson's correlation. Here, it was shown that mouthdrying perception most strongly correlated with tribology recordings at 0.00013 m/s ($r = 0.943$). This was a strong positive correlation suggesting that increased friction would be anticipated to increase mouthdrying perception. However, at this speed there was no significant difference in the instrumental friction of the samples (Fig. 7); this may explain the lack of difference seen in mouthdrying perception as no additional lubrication was provided at this sliding velocity. Contrastingly, body, mouthcoating, slippery and smoothness perception were negatively correlated with instrumental friction at 0.64 m/s ($r = -0.709$, $r = -0.783$, $r = -0.705$ and $r = -0.779$ respectively). At this speed, WPI/GG had significantly less instrumental friction than WPI/M ($p = 0.011$) and close to significantly less than WPI ($p = 0.050$) (Fig. 7), reflecting an increase in perception of mouthcoating and smoothness in the WPI/GG suspension. This correlation between tribology and sensory data supports the link between lubrication and mouthcoating perception, but suggests a speed-specific effect for each mouthfeel attribute. Therefore, our findings indicate that lubrication provided by GG signficantly influenced mouthcoating, rather than mouthdrying, perception at the levels used.

It has been previously demonstrated that mouthdrying builds up with repeated consumption (Methven et al., 2010), meaning the lack of difference may reflect the limitations of single sip analysis. The lack of influence of the partial coating of WPI with polysaccharides on mouthdrying concluded in this study should be further tested using a temporal sensory method. It was anticipated that the inclusion of mucoadhesive polysaccharides would decrease mouthdrying by advantageously competing with WPI for binding to the oral mucosa (Giles et al., 2024), but it is possible that at the concentrations used for the mucoadhesive polysaccharides were unable to outcompete WPI. Ji et al. (2023) reported changes to mouthfeel perception of WPI-oil emulsions with XG and GG in their study with 0.2% w/v XG and 0.235% w/v GG. This is significantly higher than the concentrations of XG and GG used in our study (0.03% and 0.05% respectively), supporting the suggestion that higher concentrations may be needed for this purpose. However, the WPI-polysaccharide samples were within oil-in-water emulsions in the Ji et al. (2023) study, so the results may not be directly transferrable, highlighting the need for further research in this area. However, excessive addition of polysaccharides would reduce the protein content, limiting their application as fortified beverages for older adults, meaning higher levels should be investigated with caution.

4. Conclusion

WPI is a key ingredient used within oral nutritional supplements; a common reason for disliking these products is whey protein-associated mouthdrying. The authors' previous review suggested that additional lubrication may have the capacity to reduce this mouthdrying (Giles et al., 2024). Earlier research has incorporated high levels of polysaccharides for this purpose; the current study aimed to use lower levels to increase lubrication whilst maintaining a high protein content and having a minimal impact on the sweetness of a model WPI beverage.

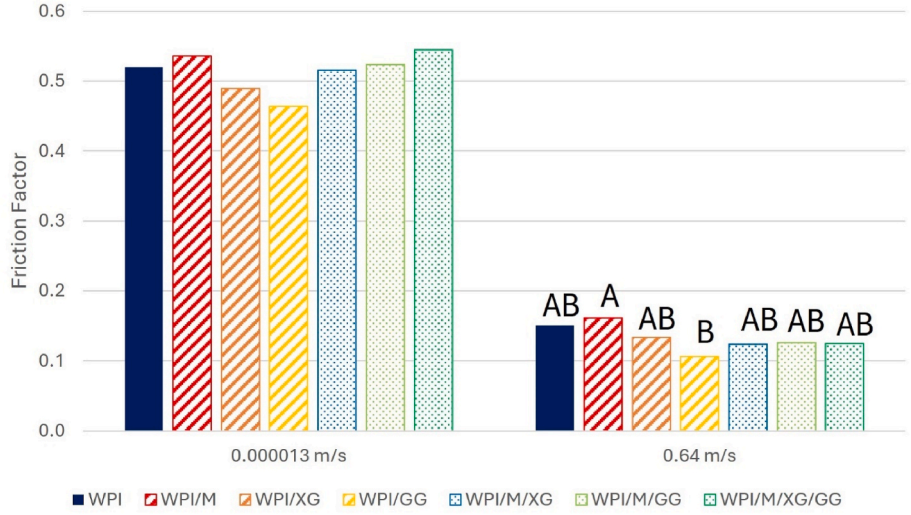

Fig. 7. Instrumental friction of 10% whey protein isolate (WPI) suspensions co-spray dried with 0.48% maltodextrin (M), 0.03% xanthan gum (XG), and/or 0.05% guar gum (GG) in isolation and in combination (0.015% XG and GG in WPI/M/XG/GG) at 0.000113 m/s when strongly correlated with mouthdrying perception and at 0.64 m/s when strongly correlated with body, mouthcoating, slipperiness and smoothness perception. Pairwise comparisons made using Tukey's test with a significance level of 0.05.

Our results show that co-spray drying WPI with XG led to an increase in viscosity and particle size, indicative of increased agglomeration. The addition of GG led to an ameliorated increase in particle size, reflecting reduced agglomeration. This subsequently led to a reduction in instrumental friction in the WPI/GG suspension, independent of viscosity changes, which was perceived by the sensory panel as more mouthcoating and smooth, compared with WPI. These sensory differences were not found upon inclusion of XG. In both our study and that of Ji et al. (2023) the addition of XG reduced friction at lower sliding speeds, due to better film formation capacity, and the addition of GG led to the greatest reduction in oral friction at higher speeds due to increased organisation and reduced agglomeration. GG increased mouthcoating and smoothness perception. However, the partial coatings of WPI achieved in our study had no significant effect on the perception of slipperiness or mouthdrying which may reflect the low levels of polysaccharides used, or the limitations of single sip profiling. Overall, this study suggests that GG is a better candidate than XG in this context, as demonstrated by the reduction in instrumental friction and influence on the sensory profile of the whey protein suspensions. Future research should investigate the full effect on mouthfeel using temporal methods to better understand the links between tribological and sensory profiles.

CRediT authorship contribution statement

Holly Giles: Writing – original draft, Methodology, Investigation, Formal analysis. **Stephanie P Bull:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Stella Lignou:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Joe Gallagher:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Marianthi Faka:** Writing – review & editing, Supervision, Resources, Conceptualization. **Julia Rodriguez-Garcia:** Writing – review & editing, Methodology, Formal analysis. **Lisa Methven:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethical statement

Ethical review and approval were not necessary for this study as the study involved tasting standard commercial practices by a trained sensory panel (n = 10; including 1 male 9 female, age from 35 to 65 years old) that are employees and have consented to taste and rate food as part of their job. Ethical approval and separate consent is only required from the trained panel where they are tasting non-standard, non-commercial or novel food ingredients. The trained panel work within the ethical and professional practices set out by the IFST: https://www.ifst.org/membership/networksand-communities/special- interest-groups/sensory-science-group/ifst-guidelines.

7. Appendices

Financial declaration

This work was funded through the UKRI BBSRC FoodBioSystems doctoral training partnership (DTP), grant reference BB/T008776/1; as an industrial Case studentship. This industry partner providing part funding was Volac Whey Nutrition Ltd, a manufacturer of whey protein ingredients with a commercial interest in increasing whey protein consumption. Volac Whey Nutrition Ltd were not involved in the evaluation or interpretation of results to ensure impartiality and only took a supervisory reviewing role.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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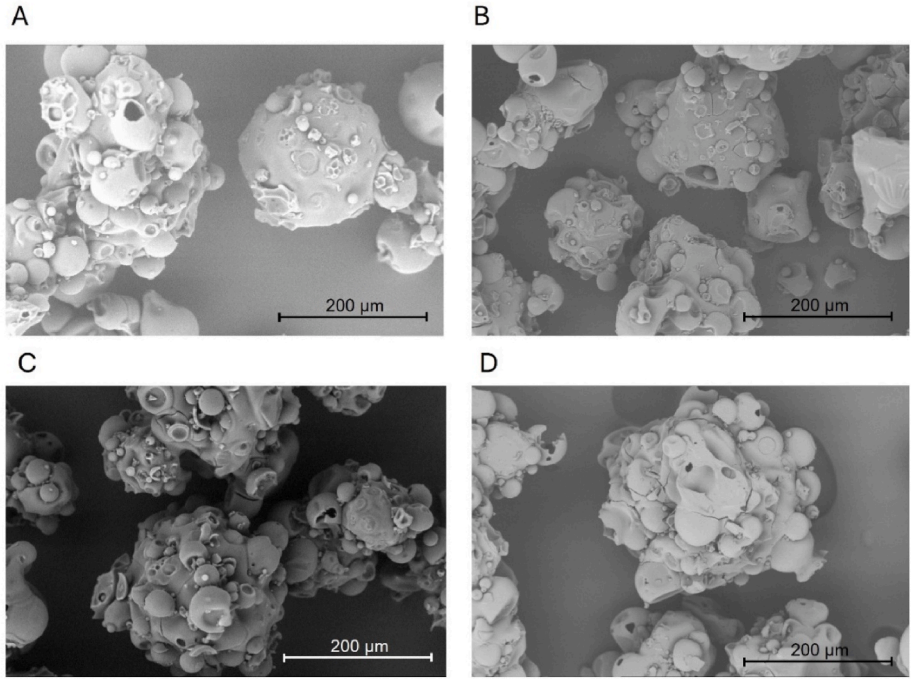
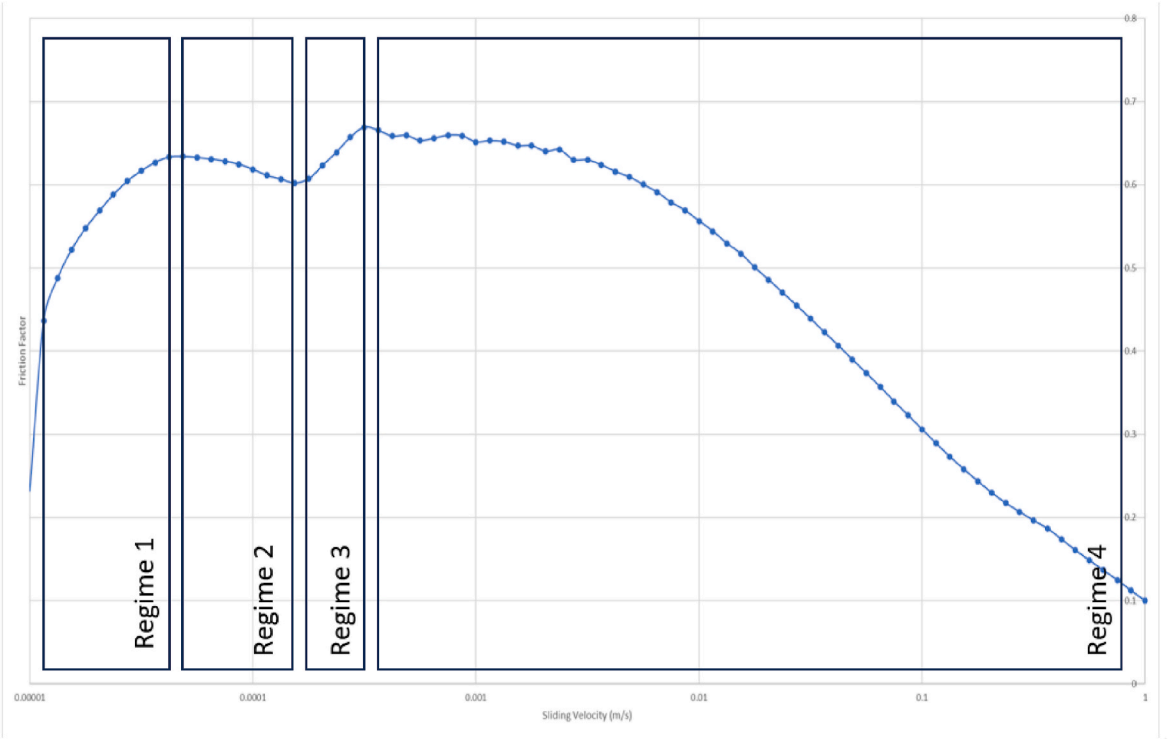


Appendix A. SEM of powders at 200× magnification; [A]: whey protein isolate (WPI) powder in isolation; [B]: WPI co-spray dried with 4.76% maltodextrin; [C]: WPI co-spray dried with 0.3% xanthan gum; [D]: WPI co-spray dried with 0.5% guar gum.



Appendix B. Tribological profile of whey protein isolate spray dried with 4.76% maltodextrin prepared in a 10% w/v aqueous suspension. Data collected during the second run.

Appendix C

Attributes scored by trained sensory panel (n = 10) for profiling 10% w/v suspensions of whey protein isolate co-spray dried with polysaccharide(s). References provided during training.

Category	Attribute	Reference/Definition	Low Anchor	High Anchor
Aroma	Powdered milk	10% skimmed 0.1% fat milk powder, Sainsbury's	None	High
	Cream	Single cream, Sainsbury's	None	High

(*continued on next page*)

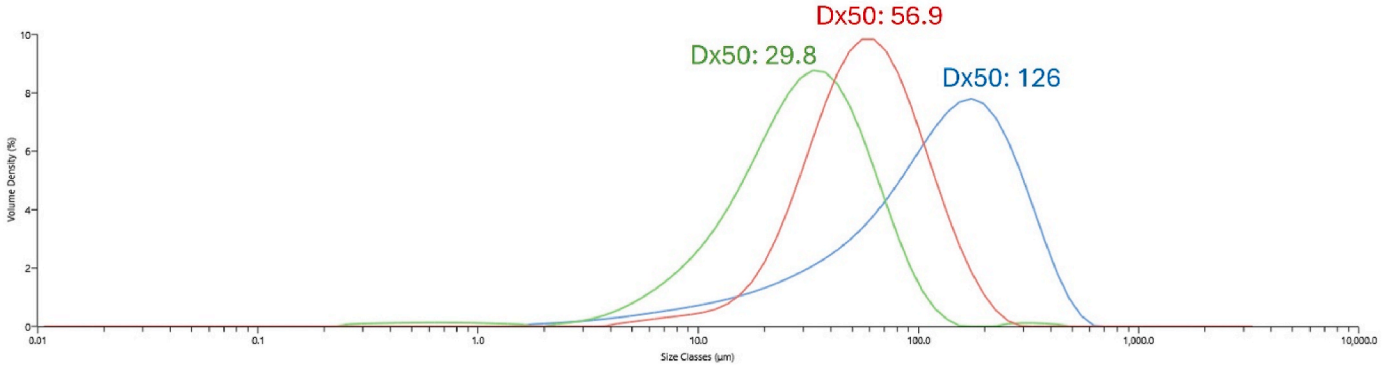
Appendix C (*continued*)

Category	Attribute	Reference/Definition	Low Anchor	High Anchor
	Mushroom	Fresh button mushrooms, Sainsbury's	None	High
	Cottage cheese	Philadelphia original soft cheese, Sainsbury's	None	High
Appearance	Lightness	Perceived lightness of colour when placed on white paper	Light	Dark
	Transparency	Ability to read text through drink when placed on paper with writing	Transparent	Opaque
Taste & Flavour	Bitter	Quinine (0.04 g/L)	None	High
	Umami	Monosodium glutamate (0.29 g/L)	None	High
	Sweet	Sucrose (5.76 g/L)	None	High
	Metallic	Iron sulphate (0.0036 g/L)	None	High
	Powdered milk	10% skimmed 0.1% fat milk powder, Sainsbury's	None	High
	Creamy	Single cream, Sainsbury's	None	High
	Cheesey	Grated mature cheddar cheese, Sainsbury's	None	High
	Mushroomy	Fresh button mushrooms, Sainsbury's	None	High
Mouthfeel	Body	Perceived thickness	Thin	Thick
	Mouthcoating	Xanthan gum (2.5 g/L)	None	High
	Mouthdrying	Tannic acid (1 g/L)	None	High
	Slippery	Guar gum (2.5 g/L)	None	High
	Smoothness	Full fat milk, Sainsbury's	None	High
After-Effect	Salivating	Amount of saliva in the mouth after swallowing	None	High
	Bitter	Quinine (0.04 g/L)	None	High
	Metallic	Iron sulphate (0.0036 g/L)	None	High
	Cheesey	Grated mature cheddar cheese, Sainsbury's	None	High
	Powdered milk	10% skimmed 0.1% fat milk powder, Sainsbury's	None	High
	Sticky Lips	Icing sugar (300 g/L)	None	High
	Drying	Tannic acid (1 g/L)	None	High

Appendix D

Average particle size of powders and 10% w/v suspensions of whey protein isolate (WPI) co-spray dried with maltodextrin (M), xanthan gum (XG) and/or guar gum (GG) taken in triplicate recordings and standard deviation (SD).

Sample	Powder		10% Suspension	
	Average	SD	Average	SD
WPI	150.33 ^{C}	3.39	16.10 ^{C}	2.35
WPI/M	143.33 ^{C}	0.47	15.90 ^{C}	0.08
WPI/XG	178.33 ^{B}	4.49	127.67 ^{ABC}	27.13
WPI/GG	196.33 ^{A}	2.49	34.30 ^{BC}	2.68
WPI/M/XG	177.00 ^{B}	0.82	164.70 ^{AB}	85.21
WPI/M/GG	177.00 ^{B}	0.82	62.13 ^{BC}	4.21
WPI/M/XG/GG	170.33 ^{B}	0.47	199.33 ^{A}	56.76



Appendix E. Particle size distribution curve of maltodextrin (blue), xanthan gum (green) and guar gum (red) powder with average particle size indicated by Dx50.

Appendix F

Average zeta potential and pH of 10% w/v suspensions of whey protein isolate (WPI) co-spray dried with maltodextrin (M), xanthan gum (XG) and/or guar gum (GG) taken in triplicate recordings and standard deviation (SD).

Suspension	Zeta potential		pH	
	Average	SD	Average	SD
WPI	−25.13	1.83	6.37	0.03
WPI/M	−25.86	2.73	6.29	0.03
WPI/XG	−22.49	5.94	6.31	0.04

(*continued on next page*)

Appendix F (*continued*)

Suspension	Zeta potential		pH	
	Average	SD	Average	SD
WPI/GG	−22.82	2.29	6.28	0.02
WPI/M/XG	−24.90	3.67	6.29	0.02
WPI/M/GG	−23.17	0.21	6.27	0.02
WPI/M/XG/GG	−21.40	0.25	6.30	0.01

Appendix G

Mean panel scores for sensory attributes of whey protein isolate (WPI) co-spray dried with maltodextrin (M), xanthan gum (XG), and/or guar gum (GG) with pair-wise comparisons (post-hoc Tukey test) shown in superscript and overall significance value given.

Attribute	WPI	WPI + GG	WPI + M	WPI + XG	WPI, M, XG, GG	WPI, M, GG	WPI, M, XG	P-Value
Aroma								
Powdered Milk	20.0 ^{B}	25.7 ^{AB}	27.1 ^{AB}	29.4 ^{A}	21.2 ^{AB}	26.8 ^{AB}	26.1 ^{AB}	0.029
Cream	4.5 ^{A}	5.5 ^{A}	6.1 ^{A}	5.6 ^{A}	6.2 ^{A}	6.2 ^{A}	5.6 ^{A}	0.878
Mushroom	6.5 ^{A}	7.4 ^{A}	12.0 ^{A}	8.3 ^{A}	7.9 ^{A}	10.5 ^{A}	10.1 ^{A}	0.337
Cottage Cheese	9.0 ^{A}	11.4 ^{A}	14.5 ^{A}	12.9 ^{A}	7.1 ^{A}	11.5 ^{A}	10.7 ^{A}	0.235
Appearance								
Darkness	47.1 ^{A}	51.4 ^{A}	50.0 ^{A}	46.9 ^{A}	45.0 ^{A}	47.2 ^{A}	48.3 ^{A}	0.330
Transparency	82.8 ^{A}	85.8 ^{A}	86.7 ^{A}	88.1 ^{A}	85.5 ^{A}	87.4 ^{A}	88.5 ^{A}	0.252
Taste								
Bitter	27.5 ^{A}	20.3 ^{A}	22.2 ^{A}	19.7 ^{A}	20.3 ^{A}	19.3 ^{A}	21.6 ^{A}	0.265
Umami	7.3 ^{A}	7.8 ^{A}	9.2 ^{A}	8.6 ^{A}	9.8 ^{A}	8.8 ^{A}	9.9 ^{A}	0.543
Sweet	12.0 ^{A}	13.4 ^{A}	14.0 ^{A}	13.8 ^{A}	16.1 ^{A}	13.5 ^{A}	13.2 ^{A}	0.522
Metallic	15.6 ^{A}	16.6 ^{A}	12.4 ^{A}	11.8 ^{A}	13.6 ^{A}	12.5 ^{A}	13.5 ^{A}	0.164
Flavour								
Powdered Milk	29.0 ^{A}	33.9 ^{A}	28.4 ^{A}	29.5 ^{A}	28.2 ^{A}	29.4 ^{A}	32.7 ^{A}	0.188
Cream	8.5 ^{A}	12.3 ^{A}	10.2 ^{A}	12.5 ^{A}	11.9 ^{A}	13.0 ^{A}	10.6 ^{A}	0.169
Cheesey	10.9 ^{A}	13.9 ^{A}	15.7 ^{A}	11.7 ^{A}	12.6 ^{A}	12.1 ^{A}	14.3 ^{A}	0.481
Mushroom	7.8 ^{B}	20.2 ^{A}	14.2 ^{AB}	16.1 ^{AB}	9.2 ^{A}	14.1 ^{AB}	11.7 ^{AB}	0.005
Mouthfeel								
Body	32.8 ^{A}	42.2 ^{A}	35.3 ^{A}	37.9 ^{A}	35.0 ^{A}	36.9 ^{A}	37.0 ^{A}	0.188
Mouthcoating	18.9 ^{B}	27.5 ^{A}	22.6 ^{AB}	25.0 ^{AB}	24.8 ^{AB}	27.6 ^{A}	25.4 ^{AB}	0.034
Mouthdrying	28.5 ^{A}	26.6 ^{A}	29.2 ^{A}	26.6 ^{A}	28.9 ^{A}	28.2 ^{A}	28.3 ^{A}	0.956
Slippery	11.3 ^{A}	19.0 ^{A}	14.1 ^{A}	18.3 ^{A}	15.5 ^{A}	17.9 ^{A}	15.5 ^{A}	0.217
Smoothness	26.6 ^{B}	36.3 ^{A}	30.2 ^{AB}	32.2 ^{AB}	32.3 ^{AB}	37.4 ^{A}	35.0 ^{AB}	0.012
After taste								
Salivating	22.2 ^{A}	26.1 ^{A}	25.0 ^{A}	24.0 ^{A}	26.3 ^{A}	26.8 ^{A}	26.2 ^{A}	0.473
Bitter	13.8 ^{A}	12.8 ^{A}	10.2 ^{A}	9.4 ^{A}	10.8 ^{A}	14.0 ^{A}	12.6 ^{A}	0.398
Metallic	11.1 ^{A}	15.3 ^{A}	9.7 ^{A}	10.1 ^{A}	11.1 ^{A}	10.4 ^{A}	11.2 ^{A}	0.143
Cheesey	6.1 ^{A}	8.3 ^{A}	8.5 ^{A}	8.1 ^{A}	7.9 ^{A}	6.5 ^{A}	8.9 ^{A}	0.726
Powdered Milk	14.2 ^{B}	21.6 ^{A}	13.6 ^{B}	17.6 ^{AB}	17.3 ^{AB}	19.1 ^{A}	18.5 ^{AB}	0.010
Sticky Lips	15.2 ^{A}	16.7 ^{A}	17.8 ^{A}	17.6 ^{A}	16.0 ^{A}	16.0 ^{A}	15.1 ^{A}	0.900
Mouthdrying	26.1 ^{A}	28.5 ^{A}	28.5 ^{A}	27.0 ^{A}	25.7 ^{A}	27.9 ^{A}	26.4 ^{A}	0.878

Data availability

Data will be made available on request.

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