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PAPER

COLLOIDAL, TRIBOLOGICAL AND SENSORY PROPERTIES OF ORAL NUTRITIONAL SUPPLEMENTS

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ABSTRACT

This study aims to evaluate the physicochemical and sensory properties of oral nutritional supplements (ONSs). High physical stability was measured in ONSs with mean particle sizes <0.33 μm and viscosity >19.3 mPa·s. ONSs formulated with dairy-soy protein mixtures displayed low friction coefficients, whereas ONSs containing dairy proteins alone had high friction coefficient values in the boundary regime. Sensory analysis revealed low to medium liking across the products and the highest preference was found in samples with the highest perceived 'sweetness', 'vanilla aroma' and 'thickness'. The results will underpin the formulation of novel ONSs with good physical stability and sensory acceptability.

Keywords: colloidal stability, oral nutritional supplement, tribology, sensory properties

1. INTRODUCTION

The global market in foods for medical purposes was valued at USD 12.3 billion in 2015 and is expected to grow because of the projected increase in nutritional deficiencies and chronic diseases, as well as the increasing global geriatric population (VMR, 2019). Foods for medical purposes are receiving increasing attention due to their ability to support the nutrient requirements of patients, to prevent and control nutrition-related diseases and to decrease medical complications and hospital re-admissions in hospitalized patients (MUELLER, 2003; SIRÓ *et al.*, 2008; CAMILO, 2003; SMITH *et al.*, 2020).
Oral nutritional supplements (ONSs) represent a specific product category, which includes beverages highly dense in macro- and micro-nutrients that are thermally treated to provide a 12 month shelf-life (MCCLEMENTS, 2015a). From a colloidal perspective, ONSs are oil-in-water emulsions in which the lipid phase, containing a mixture of vegetable oils (e.g., sunflower and soy) and lipophilic bioactive compounds, is dispersed into a water phase enriched in water-soluble vitamins, salts, polysaccharides, in addition to proteins. The proteins are derived from dairy or plant sources, and it is common that mixtures of both are used. Surface-active molecules such as proteins, polysaccharides and phospholipids are usually added to create a protective layer at the oil-water interface and prevent the oil droplets from coalescing. It is well known that oil-in-water emulsions display an inherent tendency to destabilise through a variety of physicochemical mechanisms, including gravitational separation and droplet aggregation (MCCLEMENTS, 2015a, MCCLEMENTS, 2020).
The ingredients selected in the formulation of ONSs ultimately determine their sensory properties, such as appearance, aroma and texture, which contribute to consumer liking. Previous studies have reported that ONSs possess poor sensory properties and low consumer acceptability which, in turn, can negatively affect consumption rates (GOSNEY, 2003; THOMAS *et al.*, 2018; REGAN *et al.*, 2019). Given that these beverages may function as a sole source of nutrition, this is highly problematic. Considering the importance of sensory properties and consumer acceptability for ONSs, tribology can serve as a useful instrumental means of understanding how these products are perceived during consumption in the oral cavity. Tribological parameters (i.e., coefficient of friction at the boundary and mixed regimes) have been linked to important sensory attributes, such as astringency and creaminess (MALONE *et al.*, 2003; DE HOOG *et al.*, 2006; DRESSELHUIS *et al.*, 2008; VARDHANABHUTI *et al.*, 2011; CAMPBELL *et al.*, 2017; PRIYANKA *et al.*, 2020). VARDHANABHUTI *et al.* (2011) found an increase in both astringency perception and coefficient of friction in dairy protein suspensions with increasing protein content from 0.5 to 10% w/w at acidic pH. Moreover, a strong correlation between perceived creaminess and tribological parameters as a function of fat content was identified in several studies of emulsion systems (MALONE *et al.*, 2003; DE WIJK and PRINZ, 2005).
ONSs, due to their high nutrient density, and diverse ingredient combinations, represent a highly complex food matrix and to the best of our knowledge, information on ingredient interactions, colloidal properties, physical stability and consumer acceptability of ONSs are not widely available. Therefore, the aim of this work was to undertake a comprehensive assessment of the physicochemical and sensory properties of ONSs with protein, fat and carbohydrate contents ranging from 4.0-10.0%, 2.6-6.7%, 8.7-20.4%, respectively. The information gathered will help underpin the formulation of ONSs with high physical stability and sensory acceptability.

2. MATERIALS AND METHODS

2.1. Oral nutritional supplements

Forty commercial ONSs in different flavours (e.g., vanilla, strawberry, chocolate) were procured from six different suppliers and reviewed. In order to have a broad overview of the physicochemical properties of ONS, six samples at low (~4%), medium (~6%) and high (~10%) protein content were selected for further analysis. The ONS samples were obtained from three different suppliers and all samples had a common flavour (i.e., vanilla). The ONSs were packaged in 250 mL plastic bottles, with the exception of sample A, which was packaged in a 250 mL metallic can. The samples were stored at 22±1°C prior to testing and were analysed within 4 months of their manufacture, according to the supplier information. Table 1 shows the macro-nutrient composition of the samples along with their ingredient lists.

Table 1. Macronutrient content (% w/v of product) and ingredient declaration for protein, carbohydrate and fat for the oral nutritional supplements studied A - F.

Macronutrient	A	B	C	D	E	F
Protein (%)	4.0	4.3	6.4	6.8	10.0	10.0
Ingredients	*Milk proteins, soy protein isolate*	*Milk proteins, soy protein isolate*	*Milk proteins, soy protein isolate*	*Milk proteins*	*Milk proteins*	*Milk proteins, soy protein isolate*
Carbohydrate (%)	13.5	8.7	20.4	18.8	12.4	15.0
Ingredients	*Sucrose, maltodextrin*	*Sucromalt, maltodextrin, fructo oligosaccharide*	*Sucrose, hydrolysed corn starch, fructo oligosaccharide, oat fibre, gum Arabic, carboxymethyl cellulose, soy polysaccharide*	*Sucrose, hydrolysed corn starch, gum Arabic, soy poly saccharide*	*Sucrose, maltodextrin*	*Glucose syrup, maltodextrin*
Fat (%)	3.3	3.5	5.1	2.6	6.7	5.6
Ingredients	*Canola oil, high oleic sunflower oil*	*Canola oil, high oleic sunflower oil*	*Canola oil, high oleic sunflower oil, corn oil*	*Medium chain triacyl-glycerol from palm kernel, canola and soy*	*Rapeseed oil, sunflower oil*	*Vegetable oils*

2.2. Analysis

2.2.1 Colour

Colour analysis was carried out using a tristimulus colorimeter (Chromameter-2 Reflectance, Minolta, Osaka, Japan) equipped with a CR-300 measuring head. The

instrument was standardised against a white tile before measurements. Colour was expressed in L* (luminosity), a* (green to red components for negative and positive values, respectively) and b* (blue to yellow components for negative and positive values, respectively) parameters.

2.2.2 Particle size distribution

Particle size distribution of the ONSs was determined using a laser light diffraction unit (Mastersizer 3000, Malvern Instruments Ltd, Worcestershire, UK) equipped with a 300 RF (reverse fourier) lens and He-Ne laser (λ of 633 nm). Sample was introduced to the mixing chamber and dispersed in ultrapure water until a laser obscuration of 12% (± 0.5%) was reached. The water refractive index was set at 1.33, while that of the ONSs was measured using a refractometer (Atago™ R–5000 Hand-Held Refractometer, ATAGO CO., LTD) and ranged between 1.34 and 1.38 at 20°C. Data were presented as volume-based particle size distribution together with $D_{4,3}$ values, which represent the volume mean diameter.

2.2.3 Rheological properties

The rheological properties of the selected ONSs were determined using a controlled-stress rheometer (TA Discovery Hybrid Rheometer, TA Instruments, Crawley, West Sussex, UK) equipped with a concentric cylinder geometry. Viscosity was measured as a function of shear rate in the range 1-300 s^{-1} at 22°C.
The power law (eq.1) was applied to the data obtained:

$$\tau = K\gamma^n \qquad \text{(eq. 1)}$$

where τ is shear stress (Pa), K is consistency coefficient (Pa·s^n), $\dot{\gamma}$ is shear rate (s^{-1}) and n is flow behaviour index (ANEMA *et al.*, 2014). All the curves showed an $R^2 \geq 0.99$. The results are reported as apparent viscosity at 50 s^{-1}, with this shear rate previously demonstrated to relate best to thickness perception during sensory assessments (Ross *et al*., 2019).

2.2.4 Accelerated physical stability

An analytical centrifuge (LUMiSizer®, L.U.M. GmbH, Berlin, Germany), which measures the intensity of transmitted near infra-red (NIR) light as a function of centrifugation time and position over the length of a cell held horizontally over the light path, was used to measure the rate and the extent of separation in ONSs. Polycarbonate cells (2 mm light path) were filled with 400 µL of ONSs with a wide-bore needle. Measurements were performed at 25°C and 2200g for 60 min. For calculating the change in transmission over time, integration limits were set at 109 and 130 mm. Data were reported as integral transmission (%) as a function of the running time (CROWLEY *et al.*, 2016) and the creaming rate was calculated by linear regression analysis.

2.2.5 Tribology

Tribological assessment was conducted on the selected ONSs to determine variations in friction and lubrication properties using a method as described by Batchelor *et al*. (2015). Tribological measurements were conducted using a mini traction machine (MTM2 PCS Instruments, London, UK) consisting of a 19.05 mm stainless steel ball loaded onto a 46

mm diameter silicone elastomer disc, both of which are independently driven, allowing for different motion between the two, and the temperature of measurement was maintained at 20°C. This temperature was chosen since the products are retained in the mouth for less than 20 s and therefore, it is a more representative temperature than body temperature (i.e., 37°C) (BATCHELOR *et al.*, 2015).
Stribeck curves were constructed for all of the investigated systems by measuring traction in the range 1-200 mm/s with a normal force of 2 N, which is the normal force typically applied to dairy-based products during oral processing (HORI *et al.*, 2009; MILLS *et al.*, 2013; BATCHELOR *et al.*, 2015; NGUYEN *et al.*, 2016).

2.2.6 Sensory analysis

The sensory analysis was conducted using untrained assessors (n=25) recruited from University College Cork (Ireland) in the range 21–50 years. Selection criteria for assessors were availability for testing and motivation to participate on all days of the experiment and the assessors also needed to be regular dairy beverage consumers. ONSs were coded with a randomly selected 3-digit code and presented in duplicate (STONE *et al.*, 2012). Consumers evaluated both intensity attributes and hedonic in the same session, but separated by an interval to allow training and descriptor explanation with reference to a table of descriptions provided (FELLENDORF *et al.*, 2017). The assessors were asked to rate the samples on a continuous line scale from 1 to 10 cm, in which 1 corresponded to 'extremely low descriptor intensity', and 10 to 'extremely high descriptor intensity' (Ranking Descriptive Analysis, RDA) (RICHTER *et al.*, 2010). Additionally, each assessor was asked to indicate their degree of liking on a 10-cm line scale ranging from 0 (dislike extremely) at the left to 10 (like extremely). Sessions were carried out at 22°C under white light and sensory evaluators were instructed to use still water provided to cleanse their palates between tastings.

2.3. Statistical data analysis

The results presented are the average of at least three measurements and are reported as mean value±standard deviation. Statistical analysis was performed using R v.2.15.0 (The R foundation for Statistical Computing). Bartlett's test was used to check the homogeneity of variance, one-way ANOVA was carried out and the Tukey test was used to determine statistically significant differences among means ($P<0.05$). Linear regression analysis by least squares minimisation was performed using Microsoft Excel 2007 (Microsoft Corporation, Redmond, WA, USA). The goodness of fit was evaluated based on correlation coefficients (R^2) and P values. Correlation analysis between instrumental measurements and sensory attributes was carried out using Statistica (Statistica for Windows v. 10, StatSoft, Inc.).

3. RESULTS AND DISCUSSION

3.1. Colloidal properties of oral nutritional supplements

3.1.1 Colour

Selected ONSs were firstly characterized for their colour coordinates (Table 2). High luminosity and yellowness values, indicated by L* and b* co-ordinates, with values ranging between 62.6 to 74.3 and 14.7 to 26.2, respectively, were recorded for ONS samples. Low red point values, indicated by a*, with values ranging between -0.1 and 2.8 were displayed in the samples. Similar results have been reported for nutritional beverages enriched in dairy protein and carbohydrates and have been attributed to brown melanoidin-based pigments produced in the latter stages of the Maillard reaction upon sterilisation (VAN BOEKEL, 1998; LIU and ZHONG, 2015; CHEN and O'MAHONY, 2016; DRAPALA *et al.*, 2017). LIU and ZHONG (2015) reported L*, a* and b* values ranging between 73.0 and 66.3, -2.9 and 1.2, 2.8 and 37.0, respectively, in mixtures of whey protein isolate, maltodextrin and lactose at pH 3.0-7.0 thermally treated at 130°C for 30 min. Similar results have been observed in nutritional beverages containing 8.5% milk protein isolate and 5% carbohydrate (i.e., maltodextrin, corn syrup or glucose) at near-neutral pH (pH 6.48-6.78) subjected to thermal treatment at 121°C for 15 min (CHEN and O'MAHONY, 2016).

Table 2. Chromaticity co-ordinates (L*, a*, b*), particle size mean diameter ($D_{4,3}$), rheological properties and traction coefficient for the oral nutritional supplements studied A - F.

Sample	Chromaticity co-ordinates			Particle size distribution parameter	Rheological properties		Traction Coefficient (-)	
	L*	a* (-)	b*	$D_{4,3}$ (μm)	Flow behaviour index (-)	Viscosity at 50 s^{-1} (mPa·s)	Boundary Regime (2.5 mm s^{-1})	Mixed Regime (25 mm s^{-1})
A	72.1±0.0^{d}	0.6±0.0^{d}	14.7±0.0^{f}	0.30±0.00^{c}	0.954±0.021^{ab}	7.2±0.0^{e}	0.239±0.021^{a}	0.128±0.005^{c}
B	71.4±0.0^{c}	0.6±0.0^{d}	18.5±0.0^{d}	0.31±0.00^{e}	0.801±0.001^{d}	17.3±0.0^{d}	0.221±0.025^{b}	0.143±0.014^{a}
C	68.1±0.0^{f}	0.8±0.0^{b}	22.8±0.0^{b}	8.16±0.05^{a}	0.948±0.005^{bc}	43.4±1.0^{b}	0.217±0.018^{b}	0.093±0.019^{d}
D	62.6±0.0^{e}	-0.1±0.0^{e}	26.2±0.0^{a}	2.05±0.02^{b}	0.891±0.003^{c}	19.3±0.1^{dc}	0.243±0.033^{a}	0.131±0.013^{a}
E	74.3±0.0^{a}	2.8±0.0^{a}	15.8±0.0^{e}	0.64±0.00^{c}	0.968±0.021^{a}	20.6±0.1^{c}	0.231±0.021^{a}	0.115±0.013^{ab}
F	72.7±0.0^{b}	0.7±0.0^{c}	19.7±0.0^{c}	0.37±0.00^{d}	0.927±0.003^{cd}	56.0±0.5^{a}	0.204±0.024^{c}	0.092±0.008^{d}

$^{a, b, c, d}$: means with different letters in the same column are significantly different ($P<0.05$).
n.a.: not applicable.

3.1.2 Particle size distribution

Samples A, B, E and F displayed particle size distributions with a dominant peak in the nano-sized region (0.01-1 μm) and $D_{4,3}$ ranged between 0.30 to 0.64 μm (Fig. 1A, B, E, F and Table 2). A bimodal distribution, with two distinct peaks in the nano-sized region and in the micron-sized region (1-100 μm) was observed for both samples C and D; $D_{4,3}$ values for

both samples C and D were 8.16 and 2.05 μm respectively (Fig. 1c, d; Table 2). The presence of a micron-sized peak may be attributed to hydrocolloids (i.e., including gum arabic, oat fibre and carboxy-methyl cellulose) present in the formulations, in agreement with the work of HUANG *et al.* (2001), who reported a particle size distribution similar to those in this study for emulsions containing hydrocolloids (0.5%) including methylcellulose and gum arabic. The results indicated that dairy and soy protein (i.e., A, B, E and F) aided the formation of nano-sized particle distributions, perhaps due to synergistic emulsifying properties of dairy and plant proteins when blended (HO *et al.*, 2018).

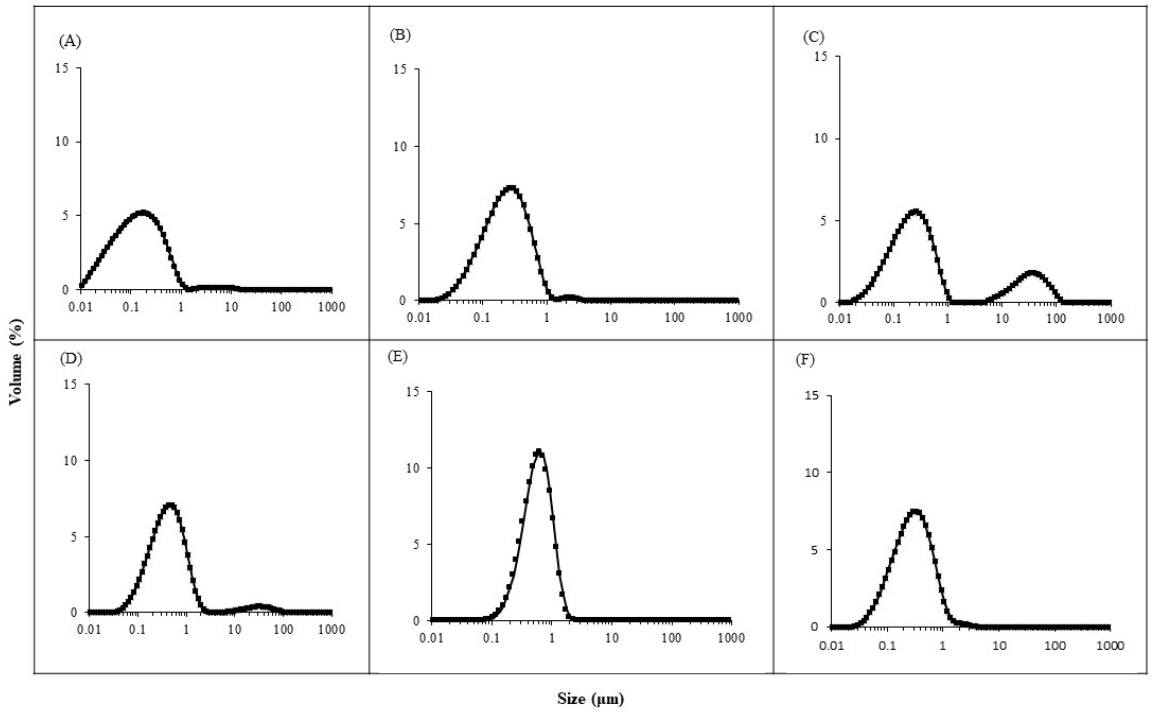


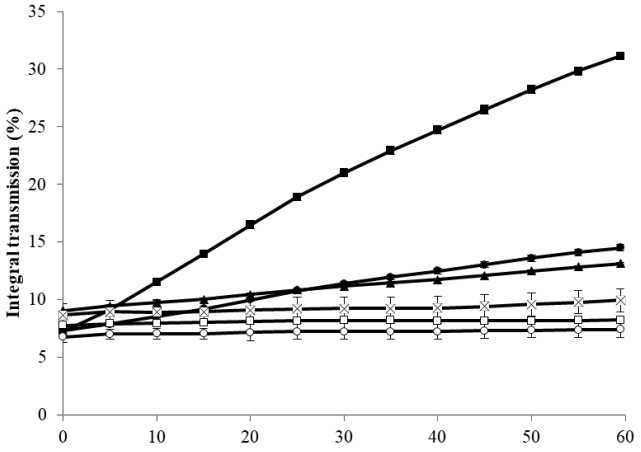
Figure 1. Particle size distribution data for the oral nutritional supplements studied A - F.

3.1.3 Rheological properties

The rheological properties, including flow behaviour index and apparent viscosity at 50 s^{-1} of the ONSs, are reported in Table 2. All the samples displayed shear thinning behaviour with flow behaviour index (n) ranging between 0.801 and 0.968. These values are typical of protein suspensions, which form weak structures that are disrupted upon application of shear stress (WALSTRA *et al.*, 2006). The viscosity ranged between 7.2 and 56.0 mPa·s across all the ONSs, with the samples ranked from lowest to highest as follows: A < B < D < E < C < F (Table 2). Samples A and B, having the lowest protein content (4%), displayed the lowest viscosity (7.2 and 17.3 mPa·s), whereas in samples D and E higher viscosity was observed with values ranging between 19.3 and 20.6 mPa·s. The highest viscosity values were recorded in ONS C and F, with values of 43.0 and 56.0 mPa·s, respectively, and may be attributed to the high proportions of carbohydrates (greater than 15%), proteins (greater than 6%) and fat (greater than 5%) in these samples (DICKINSON, 2003; PITKOWSKI *et al.*, 2009; HUPPERTZ *et al.*, 2017; QUINZIO *et al.*, 2018).

3.1.4 Physical stability

The physical stability of ONSs was investigated by measuring the changes in light transmission during centrifugation of the samples. The integral transmission as a function of centrifugation time, together with the clarification rate are shown in Fig. 2.
An increase in integral transmission with progressive centrifugation time was observed, indicative of phase separation. Samples A and B displayed clarification rates of 0.41 and 0.124 integral transmission·min^{-1} (IT%·min^{-1}), respectively, while in sample C, a slight change was observed (0.068 IT%·min^{-1}). On the other hand, no changes in the integral transmission were observed in samples D, E and F, thus indicating high stability of the ONSs (Fig. 2). The highest clarification rate (i.e., 0.41 IT%·min^{-1}), and therefore the lowest physical stability observed in sample A may be ascribed to its low viscosity (i.e., 7 mPa·s), whereas, the relatively high stability of samples C, D, E and F may be attributed to viscosity values higher than 18 mPa·s, associated with the presence of hydrocolloids (e.g., hydrolysed corn starch, oat fibre, gum arabic) in samples C and D. It is well known that hydrocolloids are able to improve the physical stability of emulsion-based systems by increasing the viscosity (MCCLEMENTS, 2015b). It has been demonstrated that the addition of guar gum from 0 to 0.5% (w/w) in an oil-in-water emulsion containing 10% oil resulted in reduction in the creaming rate from 10 to 100 min (VÉLEZ *et al.*, 2003; YOUSEFI and JAFARI, 2019).



Sample	Physical stability (Integral transmission·min^{-1})	R^2
A	0.410±0.003	0.993
B	0.124±0.003	0.999
C	0.068±0.003	0.995
D	n.a.	n.a.
E	n.a.	n.a.
F	n.a.	n.a.

Figure 2. Changes in transmission profile during centrifugation at 2200*g* for 60 min at 20°C for the oral nutritional supplements studied A (■), B (●), C (▲), D (×), E (□), F (o). Shown inset is the separation rate expressed as integral transmission·min^{-1} and R^2 computed from the slopes of the linear regression at 2200*g* for the oral nutritional supplements studied A - F.

3.2. Tribology assessment

Tribology has previously been used to model the friction and lubricity of ONSs that would occur between oral surfaces in the mouth (LAIHO *et al.*, 2017). A Stribeck curve (data not shown), which represents the traction coefficient as a function of speed motion, can be typically divided into the boundary regime (< 10 mm/s) and the mixed regime, (10-100

mm/s) which are usually associated with astringency (ROSSETTI *et al.*, 2009) and creamy textures (CHOJNICKA-PASZUN *et al.*, 2012), respectively. Within the boundary regime (<10 mm/s), systems D, A and E exhibited the greatest values of friction coefficient, with values ranging between 0.231 and 0.243, respectively, whereas samples B, C and F displayed the lowest values for friction coefficient with values between 0.217 and 0.204, respectively. According to the results, the ranking of the investigated systems from highest to lowest value at the boundary regimes was as follows: D > A > E > B > C > F (Table 2). This trend can be ascribed to different, interlinked factors, including particle size distribution, viscosity and protein type (i.e., casein and whey) as well as sources (i.e., dairy and plant) (LEY, 2008; HUGHES *et al.*, 2011; ZHAO *et al.*, 2016, VARDHANABHUTI *et al.*, 2011; MALONE *et al.*, 2003; DE WIJK and PRINZ, 2005). Conversely, in the mixed regimes (10-100 $mm \cdot s^{-1}$), lower friction coefficients indicate a creamier texture, which can be associated with sensory attributes such as thickness, smoothness, slipperiness and softness (AKHTAR *et al.*, 2006; CHOJNICKA-PASZUN *et al.*, 2012; BATCHELOR *et al.*, 2015). The ranking in terms of creamy texture, from the lowest to the highest friction coefficient at the boundary regimes, corresponding to the most to least creamy, respectively, was as follows: F > C > E > A > D > B (Table 2). This trend for texture is consistent with the composition of the investigated systems (Table 1) and was predominately ascribed to the fat content, whereby the creamier systems (i.e., F, C and E) had fat content >5% (w/w), and the less creamy systems (i.e., B, D and A) had a fat content <4% (w/w). The work of AKHTAR *et al.* (2005) showed that higher levels of fat in oil-in-water emulsions stabilized with sodium caseinate contributed to an enhanced perception of creaminess. Furthermore, the trend in friction coefficient is aligned with the apparent viscosity at 50 s^{-1} (Table 2), whereby measurement of viscosity at this shear rate is typically related to the perception of thickness (AKHTAR *et al.*, 2006; STOKES *et al.*, 2013; DICKINSON, 2018).

3.3. Sensory evaluation

The sensory profiles of the selected ONSs were mapped by ranking descriptive analysis, which included intensity of beige colour, vanilla aroma, cooked flavour, thickness and astringent after-taste (Table 3). A wide range of beige colour intensity, with values ranging between 3.7 and 7.7 was recorded for the ONS samples and the following rank, from the lowest to the highest, A < E < B < F < C < D was observed. The vanilla aroma intensity ranged between 3.8 and 7.5, with a lowest to highest ranking of B < A < E < D < F < C across the samples. Cooked flavour, which originates from sulphur compounds in thermally processed protein-based beverages, was mildly (3.3-5.1) perceived and the ONSs displayed the following rank, from lowest to highest: B < A < E < D < F < C. A positive correlation (0.847, $P<0.05$) between cooked flavour and the proportion of carbohydrate, one of the prerequisite substrates for the Maillard reaction, was found (MELLEMA and BOT, 2009). A wide range of thickness values, from 2.5 to 7.0 was recorded and the lowest thickness perception was perceived in ONSs having the lowest protein content (4.0 and 4.3% for A and B, respectively). The highest thickness values were recorded in samples C, D and F, which contained relatively high levels of protein (>6%) and carbohydrate (>15%), such as guar gum and carboxy-methyl cellulose. The results displayed a strong positive correlation between thickness perception and instrumental viscosity (0.869, $P<0.05$) as well as thickness perception and mixed regime values (-0.772, $P<0.05$), in agreement with the literature (MALONE *et al.*, 2003; DRESSELHUIS *et al.*, 2008; ROSS *et al.*, 2019).

Table 3. Data for ranking descriptive analysis and sensory hedonic evaluation of the oral nutritional supplements studied A - F.

Sample	Ranking descriptive analysis[1]						Hedonic evaluation[2]				
	Colour (degree of beige)	Vanilla aroma	Cooked flavour	Thickness	Sweet taste	After-taste	Liking of appearance	Liking of aroma	Liking of flavour	Liking of texture	Overall acceptability
A	3.7±0.1^{b}	3.8±0.2^{c}	3.9±0.7^{a}	2.5±0.2^{c}	4.3±0.3^{b}	3.4±0.1^{a}	4.9±0.0^{b}	5.5±0.3^{ab}	4.3±0.3^{b}	5.2±0.3^{b}	4.5±0.0 ^{b}
B	5.4±0.4^{ab}	5.4±0.5^{b}	3.3±0.1^{a}	4.2±0.1^{bc}	7.0±0.0^{a}	2.9±0.1^{a}	6.1±0.0^{a}	6.2±0.2^{a}	5.9±0.2^{a}	6.2±0.1^{b}	5.7±0.1^{a}
C	6.5±0.4^{ab}	4.5±0.3^{bc}	5.1±0.1^{a}	7.0±0.2^{a}	4.9±0.3^{b}	3.8±0.2^{a}	4.7±0.1^{b}	5.3±0.1^{ab}	4.1±0.3^{b}	5.1±0.1^{b}	4.0±0.2^{b}
D	7.7±0.4^{ab}	7.5±0.1^{a}	4.9±0.3^{a}	5.5±0.2^{ab}	7.4±0.8^{a}	3.0±0.5^{a}	3.6±0.0^{c}	4.9±0.1^{bc}	4.2±0.1^{b}	5.7±0.2^{ab}	4.0±0.2^{b}
E	4.0±0.4^{b}	4.4±0.2^{bc}	4.2±0.0^{a}	5.1±0.7^{ab}	5.6±0.0^{ab}	3.1±0.2^{a}	5.9±0.2^{a}	5.2±0.1^{ab}	4.9±0.1^{ab}	5.9±0.1^{ab}	5.2±0.1^{a}
F	5.5±0.1^{ab}	4.1±0.1^{bc}	5.0±0.2^{a}	6.9±0.4^{a}	6.2±0.3^{ab}	3.7±0.5^{a}	5.7±0.2^{a}	4.1±0.2^{c}	4.2±0.1^{b}	5.3±0.0^{ab}	4.0±0.1^{b}

$^{a, b, c}$: means with different letters in the same column are significantly different ($P<0.05$).

[1] corresponds to extremely low descriptor intensity; 10 corresponds to extremely high descriptor intensity.

[2] corresponds to dislike extremely; 10 corresponds to dislike extremely.

Medium sweet intensity, with values ranging between 4.3 and 7.0 was assessed across ONSs and the following order, from highest to lowest sweet intensity, A < C < E < F < B < D was observed. Across the samples, the intensity of after-taste, which is typically perceived in protein-based beverages, ranged between 2 and 3.5 and no significant ($P > 0.05$) differences were observed, probably due to the tailored ingredients balance in the formulations (DE WIJK and PRINZ, 2005; VARDHANABHUTI *et al.*, 2011). The consumer preferences for ONS products were assessed by hedonic testing, which encompasses liking of appearance, aroma, flavour, texture and overall acceptability (Table 3). ONSs displayed a medium liking score in appearance, with values ranging between 4.7 and 6.1. Sample D displayed the lowest liking in appearance (i.e., 3.6), whereas samples B, E and F showed the highest liking scores with values of 6.1, 5.7 and 5.9, respectively. Significant differences ($P<0.05$) in liking in aroma were observed within the selected ONSs and samples F and D obtained the lowest scores (i.e., 4.1 and 4.9), while B displayed the highest liking in aroma (i.e., 6.2). For liking of flavour, significant differences ($P<0.05$) across the samples were found. The liking of texture scores ranged between 5.1 and 6.2 and samples ordered, from lowest to highest as C < A < F < D < E < B. The overall acceptability reported low-medium scores, with values ranging between 4 and 5.7, in agreement with the literature for protein-based beverages (YE *et al.*, 2011; THOMAS *et al,.* 2016; WITHERS *et al.*, 2014). A negative correlation between overall acceptability and cooked flavour (-0.879, $P<0.05$) or astringent after-taste (-0.902, $P<0.05$) was observed. The panellists identified samples, namely B and E, as the most preferred products, with 48% and 23% of the preferences, respectively (Table 3). The high preference for samples B and E may be ascribed to the high sweet intensity, vanilla aroma and thickness values together with low cooked flavour and after-taste intensity recorded in the aforementioned samples.

4. CONCLUSIONS

In this study, colloidal, tribological and sensory properties were investigated in order to better understand the physical and sensory quality attributes of ONSs. Samples characterized by high viscosity and small particle size possessed the highest physical stability. ONSs containing dairy and soy protein blends with lipid content higher that 5% had low coefficient of friction values in both boundary and mixed regimes, which are usually associated with astringent after-taste and creamy texture, respectively. Low-medium liking scores were displayed across all the samples and the highest preference was recorded for samples with high sweet intensity, vanilla aroma, thickness and low values in cooked flavour and after-taste. The detailed information on rheological, colloidal, physical stability, tribological and sensory properties reported in this study will support the development of new ONSs with high physical stability and enhanced sensory acceptability.

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