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Oral processing and oral comfort appreciation of whey-enriched dairy products by older adults

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ABSTRACT

Consuming proteins rich in leucine, such as whey, has documented benefits for muscle health in older adults. The objective of this study was to evaluate the sensory suitability for this population of whey protein-enriched dairy products prototypes, resembling respectively a yoghurt and a cream cheese. Prototypes and *in vitro* boli were characterized instrumentally (rheology and tribology) and *in vivo* data on oral processing (microscopical characterization of expectorated boli) and oral comfort (sensory questionnaire) were acquired on a panel of 80 older adults. The rheological properties of both prototypes were comparable to those of some commercial yoghurt and cream cheese. Based on tribological measurements and compared to the yoghurt prototype, the cheese prototype showed higher lubrication properties, which even increased in presence of model saliva. The *in vitro* boli of cheese were also characterized by a shift in size of small particles, presumably free fat globules, into bigger particles. Microscopical observations of boli produced *in vivo* confirmed that larger fat droplets were formed by coalescence during food oral processing of the cheese prototype. In-mouth time residency and insalivation rates suggested that both prototypes required very little oral manipulation before swallowing. The sensory attributes sticky, pasty and melting were those contributing most to the oral comfort, but both prototypes were judged as very comfortable to eat independently of the dental status and salivary flow of the subjects. To conclude, these whey-enriched dairy products would be suitable as part of a diet aiming at optimizing protein intake in older adults.

1. Introduction

A decline in physical function with ageing leads to gradual loss of autonomy, but it can be modulated by modifiable factors such as physical activity or nutrition. Protein intake in particular is considered as a key nutritional factor for muscle health, with recommendations for older adults of 1.0–1.2 g/kg/day and even up to 1.5 g/kg/day in case of chronic or acute disease (Deutz et al., 2014). A meta-analysis of studies on protein intake and physical function reported that, although seemingly not preventing physical function decline with age, high protein intake is cross-sectionally associated with better physical performance in older adults (Coelho-Júnior et al., 2018). Adequate daily protein intake is therefore a goal to achieve for healthy ageing. In addition, some proteins are considered as particularly favourable to muscle health because of their high digestibility and/or high content in essential amino-acids. This is for example the case of whey proteins, rich in leucine, an amino-acid which has the potential to stimulate muscle synthesis in older adults (Katsanos et al., 2006; Rieu et al., 2006). A systematic review confirmed that supplementation with leucine or with leucine-enriched proteins such as whey improves sarcopenia evaluated through three criteria: muscle strength, lean mass and physical performance (Martínez-Arnau et al., 2019).

Even when older adults or carers are aware of nutritional recommendations, reaching a sufficient daily protein intake may be a challenge. In fact, limitation of protein intake with ageing is commonly observed for different reasons, including for example appetite loss (Dismore et al., 2024) or erroneous nutritional beliefs (Carrillo et al., 2023). Therefore, rather than increasing the amount of food ingested or

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modifying the eating habits, a promising strategy is to create familiar food products with a high content in protein. For example, by increasing the protein content of bread, drinking yoghurt or readymade meals which were consumed as part of the regular diet, protein intake was significantly increased by more than 20 % in hospitalized older adults (Stelten et al., 2015) and by approximately 25 % in community-dwelling older adults (Ziylan et al., 2017). However, a limitation to this approach is that protein-enriched products may present some sensory issues. In the case of foods rich in whey proteins, the impact is predominantly on textural and mouthfeel attributes. For example, partial replacement of wheat flour by whey proteins affected negatively the texture of protein-rich cookies by weakening the gluten network (Tang & Liu, 2017). Whey is also reported to be astringent (Sano et al., 2005), especially at low pH which is explained by interactions between positively-charged whey proteins with salivary proteins (Brown et al., 2021; Vardhanabhuti et al., 2010; Ye et al., 2011). It therefore comes as no surprise that fortification with whey is regularly associated with negative mouthfeel attributes such as "mouthdrying", mouthcoating" or "chalky" (Norton et al., 2021). In the case of older adults, this may be of particular relevance due to the higher prevalence of compromised oral health such as lower number of teeth, decreased saliva flow or xerostomia (Petersen & Yamamoto, 2005).

Keeping in mind the nutritional objective of designing familiar products rich in proteins and branched amino-acids, two dairy products with a whey-to-caseins ratio of 80:20 were developed: a yoghurt-like dessert containing 10 % (*w*/w) proteins (Lavoisier et al., 2023), and a cream cheese containing 24 % (w/w) proteins (Lavoisier et al., 2024). *In vitro* digestion of these two products using the INFOGEST static model adapted to older adults (Menard et al., 2023) evidenced that proteolysis of the whey-based products was lower in the gastric phase, but the final degree of protein hydrolysis measured at the end of the intestinal phase did not differ substantially from the values obtained on products using the conventional whey-to-caseins ratio of 20:80 (Lavoisier et al., 2023; Lavoisier et al., 2024).

The main objective of the present study was to evaluate the sensory suitability of these products for the target population, especially regarding their textural and mouthfeel attributes. For that purpose, and given the relationship between oral tribology and textural perception (Sarkar & Krop, 2019), the products and *in vitro* boli were characterized instrumentally for their rheological and/or tribological properties. The products were also assessed by a panel of community-dwelling older adults focusing on the concept of oral comfort which is of high relevance in this age group, especially in relation to oral health. Thus, this study offers a combination of objective and subjective evaluations providing a comprehensive insight on how enrichment with whey protein may affect the sensorial performance of dairy products in older adults.

2. Materials & methods

2.1. Materials

Whey proteins (Pronativ® 95) and micellar caseins (micellar casein isolate 88 %) were purchased from Lactalis Ingredients (Bourgbarré, France), the anhydrous milk fat was provided by Eurial Food Service & Industry (Nantes, France), cheese flavoring was provided by Creanova Flavors (Saint Grégoire, France). All chemicals were purchased from Sigma Aldrich unless otherwise stated.

2.2. Processing of dairy products

Two types of dairy products were prepared, resembling a yoghurt and a cream cheese. Both products were produced with a ratio of 80 % of whey proteins for 20 % of caseins. The preparation of these products is described in details in recent articles (Lavoisier et al., 2023; Lavoisier et al., 2024). Briefly, the yoghurt-like fermented product (later referred to as yoghurt prototype) was prepared by homogenizing a mixture of anhydrous fat, whey proteins and micellar caseins, heat-treating the homogenate at 72 °C for 2 min before adding the lactic ferments to the cooled preparation. Incubation was performed at 25 °C until the pH reached 4.5. The fermented product was finally stirred and stored at 4 °C. The cream cheese-like product (later referred to as cheese prototype) was prepared by stirring for 75 min at 50 °C a mixture of anhydrous fat, whey proteins, micellar caseins, salts and water before heating the mixture at 60 °C for 15 min and homogenizing it at approximately 150 bars. The homogenized mixture was transferred to 26 mm diameter synthetic casings which were immersed in a water bath at 70 °C for 35 min to form a gel, cooled down to 20 °C in an ice water bath, and stored at 4 °C.

2.3. Preparation of in vitro boli

Model saliva was prepared following the composition previously described (Sarkar et al., 2009). Briefly, to prepare 1 l of model saliva, 1.59 g NaCl, 0.328 g NH_4NO_3, 0.64 g KH_2PO_4, 0.20 g KCl, 0.31 g $K_3C_6H_5O_7.H_2O$, 0.02 g $C_5H_3N_4O_3Na$, 0.20 g H_2NCONH_2, 0.15 g $C_3H_5O_3Na$ and 3 g porcine gastric mucin type II were dissolved in distilled water. After adjusting the pH to 7.0 using 1 M NaOH, the volume was made up to 1 l using a volumetric flask. Model saliva was then added to the product: 0.14 g per gram of yoghurt prototype and 0.50 g per gram of cheese prototype, in accordance with preliminary results on insalivation rates. The mixtures were stirred at 100 rpm for 10 min to ensure dispersion while preserving the bolus structure, thereby achieving a consistency suitable for subsequent characterization. Although it is known that bovine submaxillary mucin in model saliva may replicate the human saliva lubricating properties better (Sarkar et al., 2019), pig gastric mucin was used to replicate the tribological properties of stimulated saliva which is often less lubricating.

2.4. Rheological measurements

The rheological properties of the dairy products were measured with a Modular Compact Rheometer Physica 301 (Anton Paar GmbH, Graz, Austria) equipped with a Peltier plate, and a concentric cylinder system (CC17) for the yoghurt prototype or a parallel-plate (PP50) with a rough surface for the cheese prototype. Amplitude sweeps were performed at 10 °C (to represent the usual consumption temperature of this type of dairy product) at a constant frequency of 1 Hz, between 0.01 % and 100 % strain (γ). From amplitude sweep curves, the plateau value of G' (G'0, also called gel strength) was evaluated at $\gamma = 0.1$ %, and the critical strain, corresponding to the end of the linear viscoelastic region was defined as the value of γ for which G' has dropped to 90 % of G'0. Data acquisition was performed in triplicate per product.

2.5. Confocal laser scanning microscopy (CLSM)

Microstructure of the two prototypes was observed by CLSM using a Zeiss LSM880 confocal microscope with a x63 objective (Carl Zeiss Microscopy, White Plains, NY, USA). Prior to observation, staining of proteins and lipids was achieved by incubating 200 μl of sample with 6 μl Fast Green 1 % (*w/v*) and 18 μl Red Nile 0.1 % (w/v) for 10 min at room temperature.

2.6. Tribological measurements

The evaluation of the lubrication properties of the dairy prototypes and *in vitro* boli was conducted at a controlled temperature of 37 °C using a Mini-Traction Machine (MTM2) provided by PCS Instruments, UK. The tribopair configuration involved a ball (19.0 mm diameter) on disc contact, where both surfaces were composed of polydimethylsiloxane (PDMS) with a Young's modulus of 2.4 MPa and an average surface roughness (Ra) of approximately 50 nm. Prior to the experiments, the PDMS surfaces were cleaned in an ultrasonic bath with

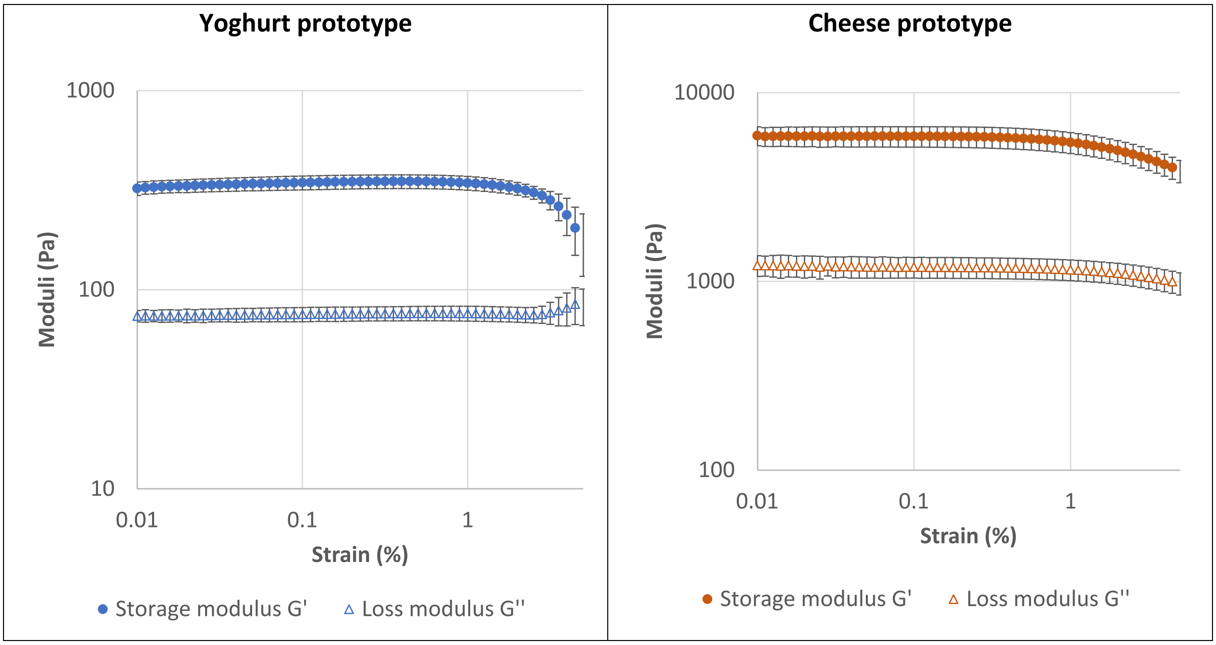

Fig. 1. Amplitude sweep curves of the two dairy prototypes.

a solution of 3 % surface-active cleaning agent (Decon 90®, East Sussex, UK), a solution of 10 % isopropanol, followed by rinsing with isopropanol. After such treatment, the surface of the PDMS retained its natural hydrophobic characteristic.

For measurement, pure sliding conditions of 50 % slide-roll-ratio (SRR) was used. A volume reducing insert was used allowing for a sample size of 15 ml. A normal force of 2 N was used allowing low contact pressure, which is of relevance in oral processing applications. Three tests of ascending sliding speed 0.1–1000 mm s − 1 were completed. The average of the three measurements is reported.

2.7. Light scattering for particle size measurements

Light scattering was used to measure the size distribution of the particles within the dairy prototypes and *in vitro* boli at 25 °C using Malvern MasterSizer 3000 (Malvern Instruments Ltd., Malvern, Worcestershire, UK). The refractive index and the dispersion medium were set at 1.469 and 1.33, respectively. The absorbance value was set 0.001 and the obscuration was 12–14 %. Results are based on three measurements on triplicate samples.

2.8. Human study

2.8.1. Subjects and sessions

Eighty participants (49 females/31 males, aged 65–89 years, mean age = 76 ± 6 y, mean BMI = 26.2 ± 3.6) participated in the study. The participants were living at home and autonomous. All participants agreed on the content of the study and signed informed consent. The dental status of each participant was determined as previously described (Feron et al., 2020) by measuring the number of Posterior Function Units (PFU), which is defined as a pair of opposing posterior teeth (premolars and molars). Salivary flow rates (ml/min) were determined with (SSF) and without mechanical stimulation (USF) at the beginning of the session as described by Neyraud et al. (Neyraud et al., 2012). Products were then served: the yoghurt prototype was served in a spoon containing 4.05 ± 0.06 g and the cheese prototype was served as 4.14 ± 0.15 g pieces to pick up with a fork. Participants were first instructed to place the product in the mouth and spit out the bolus as soon as they felt like swallowing. This was used for measurement of insalivation rate (g of incorporated saliva per g of product). Participants then tasted freely three portions of the product and responded to an oral comfort questionnaire. Observations during consumption enabled to estimate the time of residency in the mouth, calculated as the time elapsed from the placement of the food inside the mouth and the swallowing point. In addition, a session specifically dedicated to microscopical observations of the bolus was performed on 27 subjects. The bolus that they produced as described above was immediately handled following the protocol in the paragraph “fat droplet size measurement in boli”. This study was ethically approved by the COMITE DE PROTECTION DES PERSONNES (CPP) N° RCB: 2021-A02681–40.

2.8.2. Measurement of insalivation rates

Percentages of water content and dry matter in the products and in the boli were calculated by weighing samples before and after dessication at 103 °C for 24 h. From these values, for each subject and each product, the percentage of saliva incorporated into the bolus was calculated as in Repoux et al. (Repoux et al., 2012).

2.8.3. Fat droplet size measurements in boli

Microstructure images of dairy prototypes and food boli were taken with a Leica TCS SP8 inverted confocal laser-scanning microscope (Leica microsystem, Heidelberg, Germany). The sample was observed using an oil immersive x40 lens. 50 μl of a solution of Nile Red (0.04 % *w/v* in propane-1,2-diol), for fat staining, were deposited on an iBidi μDish 33 mm box, and covered by freshly collected bolus. Image acquisition was performed after an incubation of 15 min in the dark. The excitatory wavelength was 488 nm and the emission filters were set at 573 nm - 743 nm. The two-dimensional images had a resolution of 1024 × 1024 pixels and the pixel scale values were converted into micrometers using a scaling factor. The Scan speed was 400 Hz, with an applied bidirectional mode. At least five images at different locations were collected for each bolus. The images were treated with the software Las X and Image J software (version 1.53 t; National Institutes of Health, USA). The median size called D50 was calculated. This analysis was performed on boli collected from 27 subjects.

2.8.4. Oral comfort assessment

Perception of oral comfort was assessed using a questionnaire inspired from Vandenberghe-Descamps et al. (Vandenberghe-Descamps et al., 2017). This questionnaire is composed of 5 multivariate sections

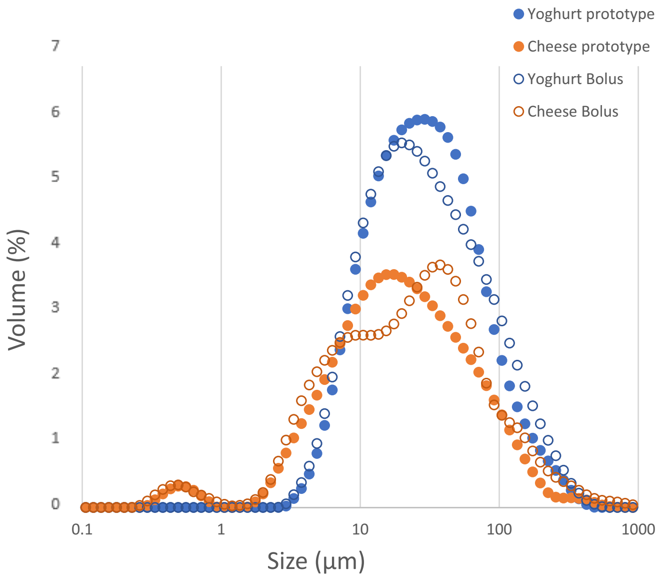

Fig. 2. Distribution of particle size (µm) in the two dairy products (filled symbols) and in products mixed with model saliva (open symbols). Particle size was measured by static light scattering.

with structured scales, each section referring to the following dimensions: overall comfort, ease of bolus formation, pain feeling, texture, flavour. For the products evaluated here, the items related to mastication were irrelevant (easy to bite with incisors, easy to bite with molars, easy to masticate), as well as the sensory attribute "stringy" which is applicable predominantly to meat products and "hard" which is applicable primarily to solid foods. Consequently, those items were not considered. Details of the questionnaire items, scales with anchors and definitions are provided as supplementary Table 1. Answers provided were converted into numerical scores ranging from 0 to 100. Participants were asked to consume one mouthful of the product for each section of the questionnaire and responded while consuming the products. Participants could drink water (Evian, France) as desired during the assessment, but had to rinse their mouth with water between the two products.

2.9. *Statistics*

Normality of the oral physiology and bolus properties data was first tested using the Shapiro-Wilk test. Since the data did not follow a normal distribution, non-parametric Spearman correlation tests were performed to assess the link between these variables. To account for the multiplicity of tests, significance of the correlations was assessed using adjusted *p*-values obtained by the Holm-Bonferroni method. Data analyses were performed using the R software, version 4.4.0.

3. Results and discussion

3.1. *Characterization of products and in vitro boli*

3.1.1. *Rheological properties*

As illustrated by Fig. 1, both samples behaved as viscoelastic gels (G' < G") in the linear viscoelastic range, with different gel strengths (G'0): ~ 350 Pa for the yoghurt prototype, and ~ 5900 Pa for the cheese prototype. Under increasing shear amplitude, both samples showed a shear thinning behaviour and the irreversible deformation of samples occurred at a critical strain (γ) of ~2.5 % for Y, and ~ 1.4 % for C. For the yoghurt prototype, gel strength was almost identical to that reported for a whey protein-enriched stirred yoghurt (Krzeminski et al., 2011). More generally, its rheological properties were comparable to those of a commercial stirred yoghurt (Lavoisier et al., 2023). Concerning the cheese prototype, its gel strength was in the same order of magnitude as the two lightest versions among 6 commercial soft cheeses (Saint-Eve et al., 2015) or an extra-light cream cheese (Macdougall et al., 2019).

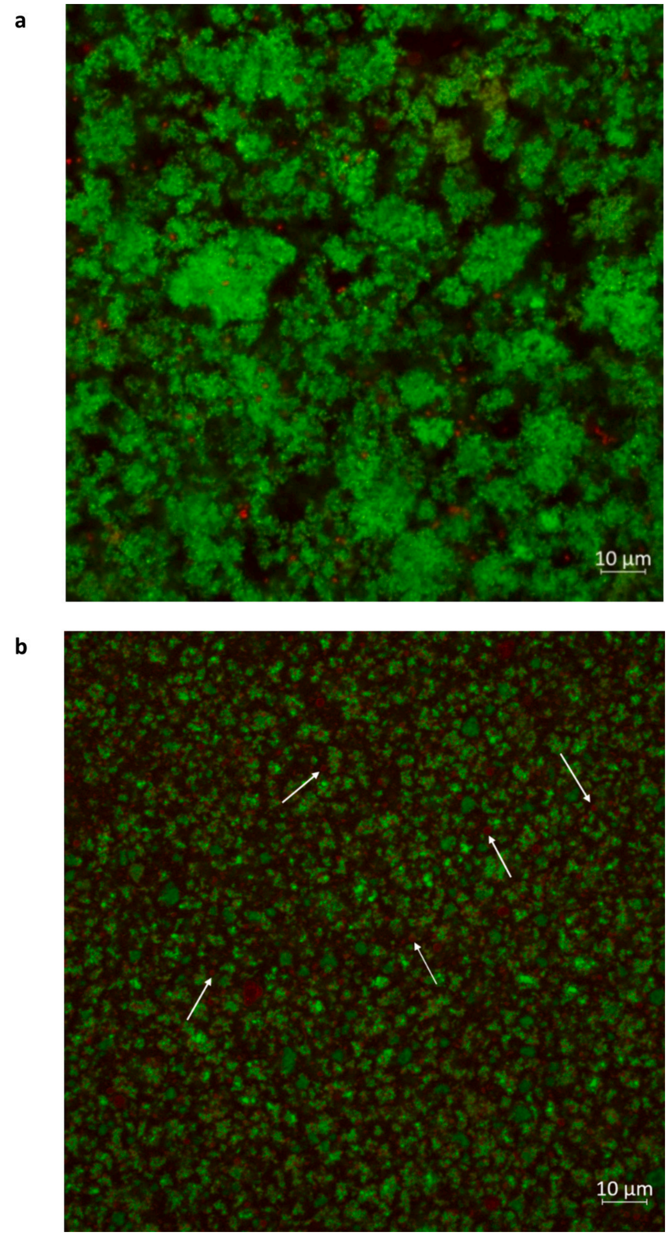

Fig. 3. Representative confocal microscopy images of the yoghurt prototype (a) and cream cheese prototype (b) after staining of proteins with 1 % (w/v) Fast Green and of lipids with 0.1 % (w/v) Nile red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1.2. *Particle size distribution*

Evaluation of particle size in the products and in *in vitro* boli, measured by light scattering, is represented in Fig. 2. The yoghurt prototype presented a monomodal distribution with approximately 90 % of the particles volume corresponding to particles between 7 and 120 µm in diameter (peak at approximately 33 µm). The cheese prototype showed a bimodal distribution, with smaller particles mostly between 0.3 and 0.8 µm and larger particles mostly between 3 and 120 µm (peak at approximately 20 µm). Addition of model saliva had a very limited impact on particle size distribution for yoghurt. This is also reflected in

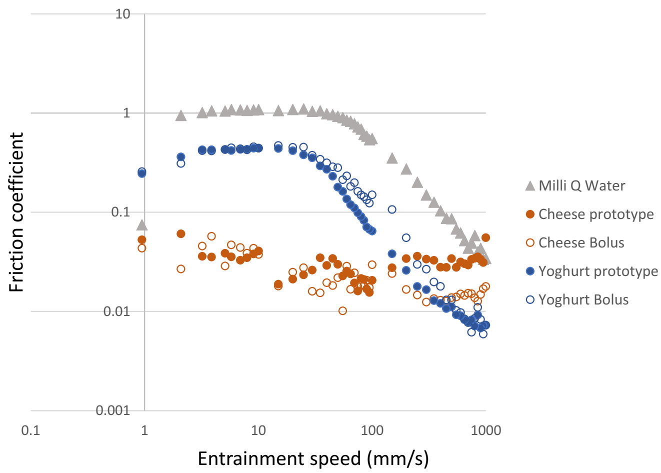

Fig. 4. Friction behaviour of water (gray triangles), of the two dairy products (filled symbols) and in products mixed with model saliva (open symbols). Data represent the mean of three independent tests per sample.

volume weighted mean diameter d_{43}, which was calculated for yoghurt since it presented a monomodal distribution. Thus d_{43} values before and after bolus preparation were 44.07 ± 8.24 µm and yoghurt boli was 49 ± 6.08 µm, respectively. For the cheese prototype, there was a slight shift of the main peak value from 20 to 37 µm, and shouldering of the curve in the area 6–15 µm, suggesting the formation of a new population of particles centered around 8–10 µm in presence of model saliva.

Microstructure of the products was also observed by confocal microscopy (Fig. 3). Confocal images confirmed that particles, corresponding mainly to protein aggregates in the yoghurt prototype (Fig. 3a) and to more intimately mixed protein-lipid assemblies in the cheese prototype (Fig. 3b), were smaller in the latter. It is likely that the smallest particles (below 1 µm) visible on the particle size distribution profile in the cheese prototype correspond to free fat globules, with examples indicated by arrows in Fig. 3b. Such fat globules are also present in the yoghurt prototype, but because of the lower quantity of fat compared to the cheese prototype (2 % *vs* 20 %), they probably represent a volume of the total particles too small to appear as a peak on light scattering profiles.

3.1.3. Tribology

The lubrication properties of the products and *in vitro* boli were evaluated using a ball-on-disk tribometer featuring hydrophobic elastomer to simulate bio-tribological contacts (Fig. 4).

The frictional performance of water is presented as control. It is characterized by high friction coefficients demonstrating lubrication to be primarily within the boundary and mixed regimes. This is expected, as water is known to be ineffective in forming a lubricating film between the hydrophobic PDMS contact surfaces. Similarly, frictional curves of the yoghurt prototype displayed two regimes, a boundary plateau at lower speeds (<20 mm/s) and a mixed regime (>20 mm/s). The reduced friction coefficient observed in the boundary regime in yoghurt compared to water was likely due to the serum phase, which primarily consists of water with some solubilized low molecular weight proteins. These proteins could move into the contact zone and "wet" the surfaces, as it is unlikely that the protein gelled particles in this product were able to enter the contact zone, as depicted in Fig. 2 where a peak particle size of 33 µm was observed. As the sliding speed increased between the two moving surfaces, hydrodynamic pressure was high enough to start to separate the moving surfaces (mixed regime) and to allow protein gelled particles to enter the contact zone, reducing the friction.

These results differ from those reported in previous studies on pot-set yoghurt (0.1% – 3.5 % fat; 3.5 % - 3.9 % protein), which showed a friction curve presenting five lubrication zones (Nguyen et al., 2017). Other studies on stirred yoghurts (fat free; 5 % protein with varying whey protein: casein ratio) have also shown a more pronounced friction reduction compared to our study (Laiho et al., 2017). Differences on lubrication behaviour might be attributed to the differences in composition compared to our samples that contained 10 % protein and 2 % fat. These compositional differences influence the degree of coalescence which is limited in our study to offer a significant lubrication benefit.

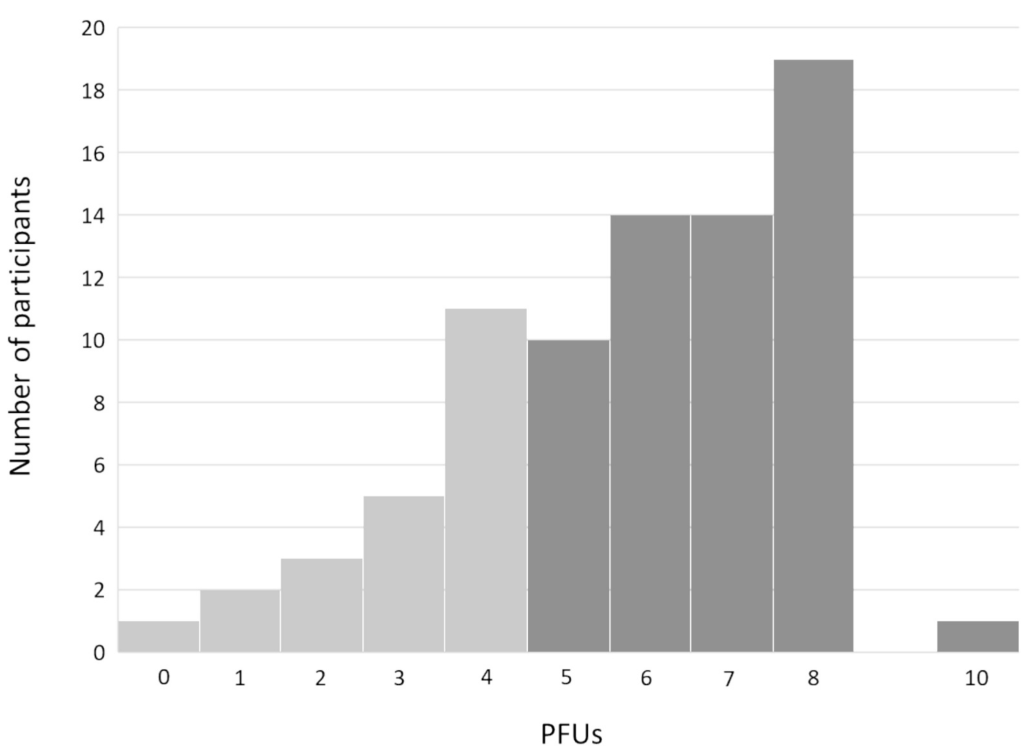

Fig. 5. Dental status illustrated by the histogram showing the frequency of the Posterior Functional Units (PFU) for all 80 participants.

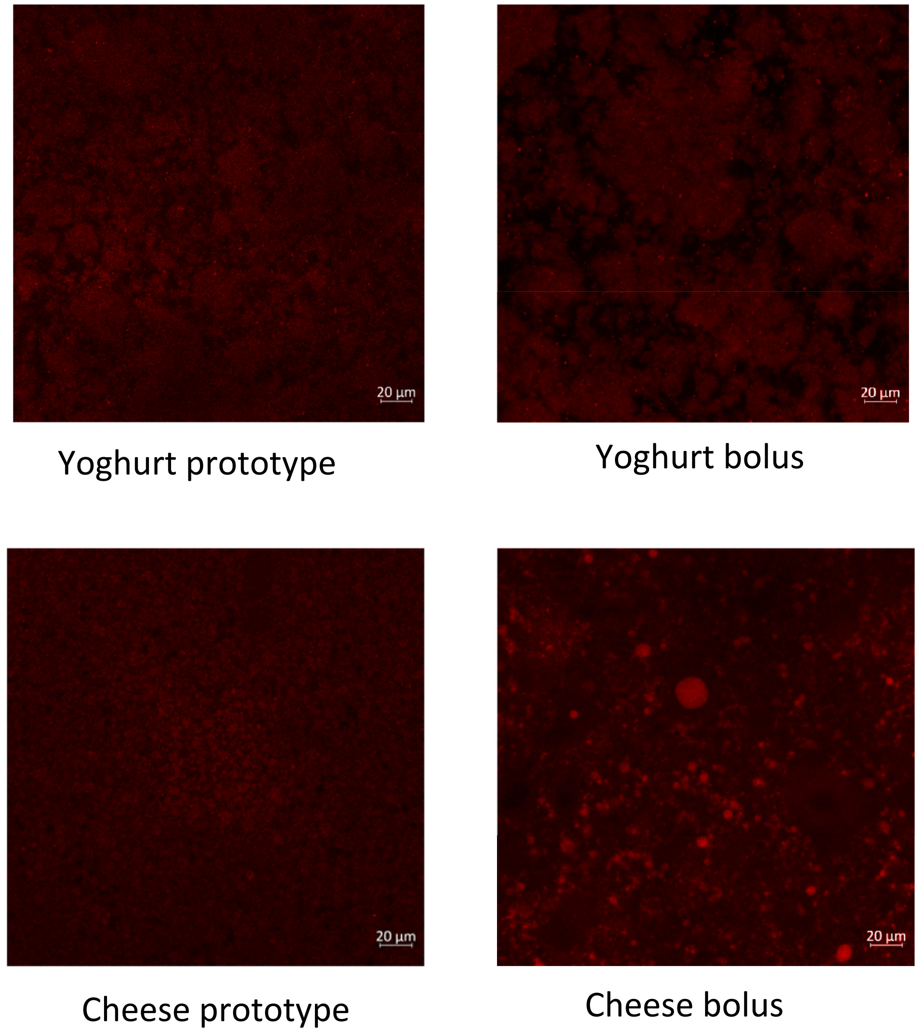

Fig. 6. Representative confocal microscopy images of boli of the yoghurt prototype and cream cheese prototype after staining of lipids with 0.04 % (*w/v*) Nile red. For comparison purposes, images of the yoghurt prototype and cheese prototype after staining of lipids are also presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the cream cheese prototype on the other hand, the friction curves did not resemble the traditional Stribeck curve. The friction coefficient (μ) was low (<0.1) across all entrainment speeds. In addition, it showed a slightly decreasing trend at entrainment speeds <100 mm/s corresponding to the behaviour of a mixed regime and a slight increasing trend when entrainment speeds exceeded 100 mm/s, indicative of the hydrodynamic lubrication regime. Since μ is dominated by the high shear viscosity of the material in the contact zone, the differences observed between the samples in this mixed regime may in part be explained by the lower viscosity measured for yoghurt compared to the cheese prototype (Fig. 1). Additionally, a similar trend in friction has been observed for flaxseed oil bodies (Kara et al., 2024), where only two regimes, mixed and hydrodynamic were present with friction coefficients values <0.05 throughout the mixed regime. Hence, it is also possible that for the cheese prototype, with higher fat content, small free fat droplets (Fig. 3b) enable a greater amount of fat to enter into the contact zone and form a lubricating coalesced film on the surfaces.

Upon mixing with model saliva to create a bolus, the lubrication performance of the yoghurt prototype showed no changed in the boundary regime, and a slight increase in friction for entrainment speed of >40 mm/s corresponding to the mixed regime. In the mixed regime, the contact surfaces are partially separated by a thin lubricating film, and the friction is influenced by both surface interactions and hydrodynamic effects. As no major changes in particle size were observed (Fig. 2), it suggests that the lubrication behaviour may be attributed to dilution effects, as addition of model saliva lowered the viscosity reducing the film's thickness, and making it harder to sustain a stable separation between the surfaces (Araiza-Calahorra et al., 2024). For the cheese prototype mixed with model saliva, the friction curve was again different from classical Stribeck curves, displaying only a mixed regime throughout the entire entrainment speed. Friction coefficients were lower in the *in vitro* bolus compared to the initial product at the higher entrainment speeds, above 200 mm/s.

Overall the tribological data suggest that the cheese would show higher lubrication properties compared to the yoghurt, in presence or not of saliva.

3.2. Human study

3.2.1. Oral status of participants

The distribution of PFUs is illustrated in Fig. 5. Based on these results, 22 subjects had a number of PFUs ≤4, which is suggested to be associated with an impaired masticatory function (Hennequin et al., 2024) and a higher risk of malnutrition (El Osta et al., 2014). The mean unstimulated salivary flow rate was 0.26 ± 0.21 g/min, with 13 subjects with a flow below 0.1 g/min which is considered to be an indicator of salivary hypofunction (Humphrey & Williamson, 2001). This mean unstimulated flow rate is slightly below the 0.3 to 0.4 g/min reported in

Table 1
Sensory scores (mean ± standard deviation) on a scale from 0 to 100.

	Yoghurt prototype	Cheese prototype
General comfort sensation		
Comfortable overall (0: very uncomfortable / 100: very comfortable)	83.4 ± 19.5	77.2 ± 22.2
Easy to eat (0: impossible / 100: very easy)	94.3 ± 11.6	88.8 ± 152
Bolus formation		
Easy to humidify (0: impossible / 100: very easy)	93.8 ± 17.0	85.8 ± 15.3
Easy to swallow (0: impossible / 100: very easy)	97.3 ± 7.6	86.8 ± 14.9
Time to swallow (0: impossible to swallow / 100: very short)	90.8 ± 11.0	77.3 ± 16.1
Pain sensation		
Causing a burning sensation (0: not at all / 100: extremely)	4.2 ± 11.1	4.6 ± 11.6
Causing muscular pain (0: not at all / 100: extremely)	0.0 ± 0.0	0.4 ± 3.7
Causing articular pain (0: not at all / 100: extremely)	0.4 ± 3.7	0.4 ± 3.7
Causing dental pain (0: not at all / 100: extremely)	0.0 ± 0.0	0.0 ± 0.0
Causing gums pain (0: not at all / 100: extremely)	0.4 ± 3.7	0.4 ± 3.7
Texture		
Sticky (0: not at all / 100: extremely)	9.2 ± 15.0	33.3 ± 21.2
Fatty (0: not at all / 100: extremely)	12.1 ± 16.1	30.0 ± 20.9
Dry (0: not at all / 100: extremely)	0.8 ± 5.2	4.2 ± 11.1
Pasty (0: not at all / 100: extremely)	21.3 ± 19.3	44.6 ± 23.1
Melting (0: not at all / 100: extremely)	58.8 ± 28.2	40.4 ± 25.8
Firm (0: not at all / 100: extremely)	2.1 ± 8.1	10.0 ± 16.3

several large studies including participants of varied ages (Dawes et al., 2015), but it is in the same order of magnitude as results obtained on a cohort of older adults with a mean age 71 yo (Chambon et al., 2021). Finally, the mean stimulated salivary flow rate was 1.70 ± 1.00 g/min, again lower than in young adults but in the range of previous studies who performed the same type of mechanical stimulation on older adults (Assad-Bustillos et al., 2019; Vandenberghe-Descamps et al., 2016). There was no association between the dental and the salivary flow characteristics, indicated by the lack of significance of the correlation between PFUs and either unstimulated or stimulated salivary flow rate (Table 2).

3.2.2. Food oral processing

Food oral processing was assessed by evaluating the consumption time, the insalivation rate of the products and the fat droplet sizes in the boli.

For the yoghurt prototype, consumption of the portion was very fast (6 ± 4.4 s) as expected for a semi-liquid product that requires no mastication and minimal handling by the tongue to initiate swallowing. Consumption time of the cheese prototype was higher (13.7 ± 6.3 s), suggesting that the product was briefly manipulated in the mouth before swallowing. The insalivation rates were in line with these values: it was very low for the yoghurt (14 % or 0.14 ± 0.1 g/g of product) and on average approximately doubled for the cheese (29 % or 0.29 ± 0.50 g/g of product). Very little values are available in the literature for insalivation rates of dairy products in older adults. In Lorieau et al. (Lorieau et al., 2018), insalivation rates of 45 % and 46 % were reported for a so-called "soft cheese" and for processed cheese, the products that would probably resemble most the prototype designed in the present study. However, time of residency in the mouth of those products were also higher (19 and 18 s on average), suggesting that the cheese prototype developed here was easier to manipulate in the mouth and necessitated little incorporation of saliva. This is consistent with the relatively high lubricating properties of this matrix evidenced by the tribological data.

Concerning fat droplets size in boli, two representative images are presented in Fig. 6. For comparison purposes, images of the two dairy products after staining of lipids are also presented.

Fat droplets in the yoghurt bolus were small in size, with mean D50 varying between subjects from 0.50 to 0.88 μm. There was little difference between the initial product and the food bolus, except that the bolus appeared a bit looser because of the dilution with saliva. Fat droplets in the cheese boli were larger, with mean D50 ranging from 4.37 to 6.94 μm. Compared with the initial product, the difference induced by food oral processing (*i.e.* mechanical constraints and saliva incorporation) was more pronounced for the cheese prototype: fat distribution was less homogenous and the presence of larger fat droplets formed by coalescence was observed. These large fat droplets may correspond to the new population of particles observed by light scattering (Fig. 2). This phenomenon of fat coalescence during food oral processing has been described in different types of food emulsions (Dresselhuis et al., 2008) but also in acid milk gels (Zhou et al., 2022). In food emulsions, higher sensitivity to coalescence was linked to an enhanced perception of various fat attributes (creamy mouthfeel, fatty, slippery…) and to a lower experimentally measured friction (Dresselhuis et al., 2008). This decreased friction when the product was mixed with saliva was also observed in the tribological test (Fig. 4) at the highest entrainment speed above 200 mm/s.

3.2.3. Sensory assessment of oral comfort

Mean sensory scores of the oral comfort questionnaire are shown in Table 1.

Both products were judged very comfortable and easy to eat, although the two scores for comfort were slightly lower for the cheese prototype, probably in relation to the higher scores for texture attributes such as sticky, pasty or firm. The scores for the descriptor "rapid to swallow" were in line with the *in vivo* observations of in-mouth time residency and the scores for the "fatty" attribute reflected the higher level of fat in the cheese prototype. Both products caused virtually no oral pain. Finally, a commonly reported mouthfeel defect in whey-enriched products, particularly those with low pH, is their astringency (Norton et al., 2021). This specific attribute is not included in the oral comfort questionnaire, but it can be partly covered by the attributes "burning" since astringency is a trigeminal sensation, or "dry" in the relation to the mouth drying feeling associated with astringent foods. It is for example interesting to note that these two attributes were correlated (Table 2) for the yoghurt prototype, *i.e.* in the product containing less fat and more acidic, where astringency is more expected to occur. In any case, the scores for these attributes were very low for both products.

3.2.4. Links between oral physiology, food oral processing and oral comfort

Correlations between oral physiology data (PFUs, SSR, USR), food oral processing data (in-mouth time residency, insalivation rates, fat droplet D50) and selected sensory scores were evaluated by Spearman correlation. Tables 2 and 3 present the results for the yoghurt and cheese prototypes, respectively.

Unstimulated and mechanically stimulated salivary flow rates were positively and significantly correlated, in accordance with Engelen et al. (Engelen et al., 2003). The stimulated salivary flow rate was also positively correlated with the insalivation rate for the yoghurt prototype, which is somehow unexpected since this product remains very little time in the mouth and induces less mechanical stimulation than the firmer cheese prototype. Acidity or astringency of the yoghurt prototype may be involved in this correlation.

Generally, the oral physiology and food oral processing characteristics were not correlated to any of the comfort or sensory attributes for both products. This confirms some of our previous results, where using the same questionnaire on a wider product range (meat, dairy and cereals), it was shown that there was no significant effect of oral health (dental status and salivary flow) on global oral comfort whatever the products (Vandenberghe-Descamps et al., 2017). The different comfort-related attributes were strongly positively correlated to each other, at the exception of the attribute "rapid to swallow" which did not appear correlated with overall comfort, neither in yoghurt nor in cheese. Some

Table 2
Correlations between oral physiology data (PFUs, SSR, USR), food oral processing data (in-mouth time residency TR, insalivation rate IR, fat droplet D50) and selected sensory scores, for the yoghurt prototype. Only significant correlations are reported ($p < 0.05$): Spearman correlation coefficient and adjusted *p*-value (Holm-Bonferroni's method).

	USR	SSR	TR	IR	D50	overall comfort	easy to eat	easy to humidify	easy to swallow	rapid to swallow	burning	sticky	fatty	dry	pasty	melting	firm
PFUs																	
USR		0.486 *p* = *0.007*															
SSR				0.281 *p* = *0.033*													
TR																	
IR																	
D50																	
overall comfort							0.530 *p* < *0.001*		0.408 *p* = *0.024*						−0.519 *p* < *0.001*		
easy to eat								0.448 *p* = *0.004*	0.705 *p* < *0.001*	0.408 *p* = *0.024*							
easy to humidify									0.546 *p* < *0.001*								
easy to swallow										0.438 *p* = *0.007*							
rapid to swallow																0.403 *p* = *0.029*	
burning														0.424 *p* = *0.013*			
sticky															0.432 *p* = *0.009*		
fatty																	
dry																	
pasty																	
melting																	

Table 3
Correlations between oral physiology data (PFUs, SSR, USR), food oral processing data (in-mouth time residency TR, insalivation rate IR, fat droplet D50) and selected sensory scores, for the cheese prototype. Only significant correlations are reported ($p < 0.05$) Spearman correlation coefficient and adjusted p-value (Holm-Bonferroni's method).

	USR	SSR	TR	IR	D50	overall comfort	easy to eat	easy to humidify	easy to swallow	rapid to swallow	burning	sticky	fatty	dry	pasty	melting	firm
PFUs																	
USR		0.486															
		$p = 0.007$															
SSR																	
TR																	
IR																	
D50																	
overall comfort							0.606	0.499	0.638						−0.391		
							$p < 0.001$	$p < 0.001$	$p < 0.001$						$p = 0.047$		
easy to eat								0.562	0.543								
								$p < 0.001$	$p < 0.001$								
easy to humidify									0.761	0.581		−0.433				0.449	
									$p < 0.001$	$p < 0.001$		$p = 0.008$				$p = 0.004$	
easy to swallow										0.533		−0.450					
										$p < 0.001$		$p = 0.004$					
rapid to swallow																	
burning																	
sticky															0.514		
															$p < 0.001$		
fatty																	
dry																	
pasty																	
melting																	

sensory attributes explained some of the oral comfort ratings: in yoghurt, the "pasty" nature of the product was negatively correlated to overall comfort, and "melting" was positively associated to the speed of swallowing. In cheese, a higher "sticky" character impacted negatively the ease to humidify and swallow the product. Like in yoghurt, "pasty" was negatively associated to overall comfort. Finally, "melting" was positively associated with "easy to humidify".

The sensory attributes pasty and sticky were positively correlated to each other in both products, and as previously discussed above, the dry and burning sensation ratings were positively linked to each other in the yoghurt prototype, most likely explained by the contribution of such attributes to astringency.

Taken altogether, those results highlight that for the dairy products developed here, the sticky, pasty and melting sensory attributes were those that accounted most to the perception of different attributes related to oral comfort.

3.2.5. *Relevance to the food or healthcare sectors*

This study showed that it was possible to design whey-enriched products with textural properties resembling that of commercial familiar products. This differentiates these products from protein-rich medical supplements such as drinks or custards, which are usually prescribed for severe protein malnutrition. The developed prototypes were rather conceived as products supporting the prevention of protein malnutrition through usual diet. The marketing challenge for the food industry would remain to promote such products with appropriate communication strategy to reach the targeted audience (older adults and/or catering services in older adults' residential places).

4. Conclusion

Two whey-enriched products were successfully developed. Their rheological properties were comparable to those of some commercial milk-based versions. Tribological tests indicated that the cream cheese prototype was more lubricating than the yoghurt prototype, but overall comfort was rated very high for both products. In addition, qualitative appreciation of the products did not depend on the dental or salivary status of the consumers or their way of handling the products in the mouth. This is of special interest for products targeted at a population of older adults, where variability in oral health is higher than in the general population. Although further development is needed to optimize the other sensory attributes of the products, such as taste or flavour, this work suggests suitability of whey-enriched dairy products as part of a diet aiming at optimizing protein intake in older adults.

CRediT authorship contribution statement

Andrea Araiza Calahorra: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Bérénice Houinsou-Houssou:** Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Anwesha Sarkar:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Anaïs Lavoisier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Hélène Labouré:** Writing – review & editing, Supervision, Data curation. **Chantal Septier:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Cindy Sounouvou:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Carole Tournier:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Gilles Feron:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization. **Martine Morzel:** Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gilles Feron reports financial support was provided by French National Research Agency. Martine Morzel reports financial support was provided by French National Research Agency. Anwesha Sarkar reports financial support was provided by Biotechnology and Biological Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2025.117468.

Data availability

Data will be made available on request.

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