Ribes, S.; Estarriaga, R.; Grau Meló, R.; Talens Oliag, P. (2021). Physical, sensory, and simulated mastication properties of texture-modified Spanish sauce using different texturing agents. Food & Function. 12(17):8181-8195. https://doi.org/10.1039/d1fo00742d

https://doi.org/10.1039/d1fo00742d

Physical, sensory, and simulated mastication properties of texture-modified Spanish sauce using different texturing agents

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Abstract

This study aims to evaluate colour, texture, flow, viscoelastic, sensory, and simulated mastication properties, in presence and absence of artificial saliva, of texture-modified Spanish sauce at different temperatures (25 ºC, 37 ºC and/or 55 ºC). Sauce texture was modified using five hydrocolloids (modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC), and chia seed mucilage (CSM) as alternative texturing agent), achieving two well-differentiated consistencies: honey-like and pudding-like consistencies. The MS, GG, TG and CSM sauces showed greater consistency, firmness, stiffness, and resistance to flow than CMC samples. Furthermore, the internal structure of CMC sauces was the most affected by temperature changes. The addition of saliva decreased the apparent viscosity, consistency, and adhesiveness of sauces. Among the samples studied, GG and CSM texture-modified sauces would be suitable for dysphagic patients because of their good elasticity degree, relatively high resistance to deformation and structural stability, as well as better resistance to salivary α-amylase action. However, CSM sauces obtained the lowest sensory attributes scores. This work opens doors to the use of CSM as texturing agent and demonstrates the importance of considering the hydrocolloids type and consistency-level, but also the administration temperature of dysphagia-oriented products. Selecting the proper texturing agent is of great importance for the safe and easy swallowing of dysphagic patients.

Keywords: dysphagia; texture-modified products; rheology; sensory analysis; mastication assay; saliva

1. Introduction

Oropharyngeal dysphagia (OD) is a dysfunction of the digestive system, which consists of a difficulty in swallowing, affecting the correct transit of the bolus in the upper digestive tract.[1] One of the most employed strategies to overcome this problem is the use of texturing agents that modifies foods texture. In this context, the National Dysphagia Diet Task Force establishes different products' consistencies based on their viscosity, which is determined at a shear rate of 50 s^{-1} and at 25 ºC, as follows: nectar-like consistency (51-350 mPa·s); honey-like consistency (351-1750 mPa·s); and pudding-like consistency (>1750 mPa·s).[2]

Most of the texturing agents available on the market are composed of modified starch, gums or maltodextrins[1,3,4]. In this study, modified starch (MS) and three gums, two galactomannans such as guar gum (GG) and tara gum (TG), and sodium carboxymethylcellulose (CMC), which were used in a prior study[5] with good results, were tested. Starch is a naturally available and low-priced thickener but it is partially hydrolysed in the mouth by the salivary α-amylase, lowering samples' viscosity.[1,4] Gums are not hydrolysed by this enzyme, maintaining the viscosity more stable during the swallowing procedure[1] GG and TG are widely employed as texturing agents for dysphagia management due to their excellent characteristics.[3] GG produces high viscosity solutions with pseudoplastic behaviour at low concentrations, and TG is similar to GG in terms of structure and functional features, but its organoleptic properties are deemed to be better than that of GG. Furthermore, the high price of GG has increased the interest of TG as texturing agent.[6] CMC has been employed in several dysphagia applications since it confers clear and odourless solutions with high viscosity values.[4] In the last years, a growing interest in the use of different plant-based hydrocolloids as natural texturing agents has been observed. Vieira *et al.*[1] evaluated the rheological and tribological properties of flax seed gum, the soluble polysaccharide fraction extracted from *Linum usitatissimum*, with the aim of confirming its use as potential thickener in the treatment of dysphagia. Similarly, chia seeds (*Salvia hispanica* L.) produce a transparent mucilaginous gel in contact with water, essentially composed of soluble fibre. This gel presents an excellent water retention capacity and good viscosities, even at low concentrations.[7] These technological properties make chia seed mucilage (CSM) a promising candidate for food applications as commercial texturing and gelling agents. However, its use as texturing agent in the development of products for patients with swallowing difficulties has not been investigated. In this study, CSM has been incorporated as alternative texturing agent to starch and gums.

Other factors should be taken into consideration when designing dysphagia-oriented products. Temperature affects the samples' thickness.[8] Nevertheless, while many works have been assessed the gelling properties of hydrocolloids, few literature is available about the impact of temperature on the mechanical and rheological properties of dysphagia-oriented products. Furthermore, saliva is crucial in bolus cohesiveness and affects its viscoelastic properties.[9,10] During food oral processing, products are mixed with saliva, which contains α-amylase, responsible for the breakdown of starch components and viscosity reduction. These viscosity changes can increase the risk of aspiration in dysphagic patients.[11]

Spanish sauce, a brown sauce widely used in French and Spanish cuisine that serves as base for a wide variety of derived sauces, has been employed in this study. This classic sauce allows many variations, but it is made up of onion, carrot and other vegetables, oil, meat broth, wine and, optionally, some flour to modify its texture. The main objectives of this work were to: i) evaluate the colour, texture, flow, viscoelastic and simulated mastication properties of different texture-modified Spanish sauces as a dysphagia-oriented product; ii) study the use of CSM as an alternative texturing agent for dysphagia compared to modified starch or common gums; iii) investigate the influence of temperature on the flow behaviour and structural changes of samples; iii) determine the impact of saliva during samples mastication; and iv) evaluate the sensory acceptance of each texture-modified Spanish sauce.

2. Materials and Methods

2.1 Materials

For the Spanish sauce preparation, onion, carrot, crushed tomato, meat broth, white wine, olive oil, and sodium chloride were purchased from a local Spanish market.

In order to modify the texture of the homemade sauce, five different hydrocolloids were employed: Modified starch (Nutavant®, MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM). Nutavant®, a commercial starch based thickener used in dysphagia management, was purchased from a local Spanish pharmacy. GG and CMC were supplied by EPSA (Valencia, Spain), and TG was provided by Cocinista (Madrid, Spain).

For artificial saliva preparation, potassium chloride, potassium phosphate, sodium bicarbonate, magnesium chloride hexahydrate, ammonium carbonate, calcium chloride dihydrate, porcine stomach mucin Type II, and porcine pancreatic α-amylase were supplied by Sigma-Aldrich, Co. Ltd (St. Louis, MO, USA). The use of the pancreatic α-amylase was based on previous studies on food oral processing.[12]

2.2 Mucilage extraction from chia seeds

The CSM was extracted from commercial chia seeds (Pedon S.P.A, Molvena, Italy) according to the methodology described by Ribes *et al.*[7], with minor changes. Chia seeds were mixed in distilled water (seed:water: ratio of 3:30) and stirred for 3 h at 60 °C in an electrical food processor (Thermomix TM 31, Vorwerk M.S.L, Spain). The mixture was centrifuged at 12,857 g for 10 min at 20 °C (Centrifuge 5804 R, Eppendorf AG, Hamburg, Germany). Lastly, the CSM was freeze-dried (LyoQuest-55, Telstar, Terrassa, Spain) for 48 h and kept in plastic vessels at room temperature before using.

2.3 Homemade sauce manufacture

The homemade sauce was prepared by cooking (100 ºC, 30 min) and blending (speed 10, 2 min) the following ingredients in an electrical food processor (Thermomix TM 31, Vorwerk M.S.L, Spain): onion (20%, w/w), carrot (5%, w/w), crushed tomato (6%, w/w), meat broth (50%, w/w), olive oil (6%, w/w), white wine (10%, w/w), and sodium chloride (3%, w/w). Texture-modified sauces were obtained by adding and mixing the above-mentioned hydrocolloids with the use of a magnetic stirrer at 70 ºC, until ensuring their dispersion. Concentrations (%, w/w) of each hydrocolloid employed to prepare the samples, as well as their resulting apparent viscosities, measured at 25 ºC with a shear rate of 50 s^{-1},[2] are summarised in Table 1. Based on this, the texture-modified sauces were classified as honey-like (*ca*. 1350 mPa·s) or pudding-like consistencies (*ca.* 2400 mPa·s). All texture-modified sauces were prepared 24 h before testing, poured into plastic containers, and stored at 4 °C until analysed at 25 ºC, 37 ºC and 55 ºC. These conditions were selected to simulate the temperature employed by the NDDTF,[2] the temperature of the oral cavity and the food serving temperature employed in long-term care centres, respectively.[2,4,10] Two independent batches were prepared for all the samples.

2.4 Artificial saliva preparation

The artificial saliva employed in this study was prepared based on the standard consensus protocol for static simulated digestion released by Infogest,[13] with minor changes. Simulated salivary fluid, containing potassium chloride (1.126 g/L), potassium phosphate (0.503 g/L), sodium bicarbonate (1.142 g/L), magnesium chloride hexahydrate (0.03 g/L), ammonium carbonate (0.0057 g/L), calcium chloride dihydrate (0.221 g/L), porcine stomach mucin Type II (3 g/L) and porcine pancreatic α-amylase (75 U/mL), was mixed with the samples in a ratio 1:1 (v/w).

2.5 Colour and texture characterisation of samples

Colour parameters (L*, a*, and b*) of samples were measured by a spectrocolorimeter (CM-3600d, Minolta Co., Tokyo, Japan) with an observer 10º and illuminant D65. For avoiding sample's translucency, the measurements were taken by using a white and a black background. The infinite reflectance (R∞) of the samples was obtained by applying the Kubelka–Munk theory. Colour variations (ΔE*) of the texture-modified sauces compared to the unmodified sauce were calculated by using Eq. (1):

$$\Delta E^{*} = ((\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2})^{0.5} \qquad (1)$$

Samples texture was measured by performing a back extrusion test in a TA.XT2 Texture Analyser (Stable Micro Systems, Godalming, UK) following the method described by Gallego *et al.*,[14] with minor modifications. The samples were poured into a glass measuring container, filling up to 40 mm of height. A cylindrical probe of 35 mm of diameter was employed to press the samples to a depth of 12 mm, with a test speed of 2 mm/s. The force *vs* distance plot generated was used to obtain the following parameters: i) maximum force, related to the firmness of the sample; and ii) area under the curve, related to the consistency of the sample.

All the tests were run at 25 ºC, 37 ºC and 55 ºC in duplicate. The samples were maintained in a water bath for 30 min before conducting the tests.

2.6 Flow and viscoelastic measurements of samples

A rotational Kinexus Pro + Rheometer (Malvern Instruments Ltd., MA, USA), with a Peltier heating system for precise temperature control, was used to perform the flow and viscoelastic measurements of the texture-modified sauces. Assays were conducted at 25 °C, 37 ºC and 55 °C using the PLC61/PU40 parallel-plate geometry with a 1 mm gap. Samples were allowed to stand for 120 s for structure recovery before being tested. Silicone oil was employed for preventing water evaporation from samples. All the measurements were done in duplicate.

2.6.1 Flow rheological properties

To study the steady flow behaviour of the texture-modified sauces, flow curves were obtained as a function of the shear rate, ranging from 0.1 to 200 s^{-1}, for 300 s. The flow curves were fitted to the power law model, and the consistency coefficient (K) and the flow behaviour index (n) were determined.[5] The correlation coefficient R^2 was employed to verify the goodness-of-fit.

Furthermore, the influence of temperature on the apparent viscosity of the samples was described by Arrhenius Eq. (2):

$$\eta = A \cdot \exp\ (Ea/RT) \tag{2}$$

where η is the apparent viscosity at 50 s^{-1} (Pa·s), A is the pre-exponential constant (Pa·s), Ea is activation energy (J/mol), R is gas constant (8.314 J/mol K), and T is temperature (K).

2.6.2 Viscoelastic properties

The viscoelastic properties of samples were characterised by non-linear and linear viscoelastic assays. A large amplitude oscillatory shear test (LAOS) was conducted to determine the limits of the linear viscoelastic region (LVR) and to characterise the non-linear viscoelastic properties of the texture-modified samples. Stress sweep test was performed within a stress range from 0.1 to 100 Pa at 1 Hz. From this test, the changes in elastic modulus (G') and viscous modulus (G'') with the stress, and the elastic modulus value at LVR (G'_{LVR}), the stress value at LVR ($Stress_{LVR}$), and the flow point, as the value of the shear stress at the crossover point where G' = G'', were reported. The limit of the LVR was determined as the stress (Pa) at which the G' value was reduced from 100% to 90% of G' plateau value.[4]

The linear viscoelastic properties of the texture-modified sauces were characterised by a small amplitude oscillatory shear test (SAOS). A frequency sweep test was conducted at 0.25 Pa (in the LVR) to cover a 0.1-100 Hz frequency range. The viscoelastic parameters, elastic modulus (G'), viscous modulus (G''), complex modulus ($|G^*|$), complex viscosity ($|\eta^*|$) and loss tangent (Tan δ), were obtained from the rheometer software (rSpace for Kinexus).

To determine the influence of the temperature on the structural changes of the samples, a temperature sweep test was performed from 20 ºC to 80 ºC at a heating rate of 5 ºC/min. Measurements were run within the LVR (0.25 Pa) and at a frequency of 1 Hz.

2.7 Simulated mastication assay

The simulated mastication assay of texture-modified sauces was carried out according to the methodology described by Chung *et al.*[15]. The rotational Kinexus Pro+ Rheometer (Malvern Instruments Ltd., MA, USA), with a Peltier heating system and a PLC61/PU40 parallel-plate geometry, was employed. The samples were compressed, sheared and decompressed for ten cycles to mimic the movement of the tongue and palate during consumption.[5,15] The assay was carried out at 37 ºC in presence and absence of artificial saliva (food:artificial saliva ratio, 1:1), for determining its impact on samples during chewing.

2.8 Sensory evaluation

The sensory evaluation of the texture-modified sauces was performed by a semi-trained panel. The participants were between 23 and 50 years old and comprised 24 women and 10 men. Panellists were recruited based on their interest in the sensory evaluation of oriented-dysphagia products, availability, and lack of allergies, following the general guidelines of UNE-ISO 8586:2012[16] and IFST Guidelines for Ethical and Professional Practices for the Sensory Analysis of Foods.[17] Furthermore, every panellist gave written consent before conducting the sensory analysis. Testing was carried out after different training sessions, which allows introducing the assessors to the sensory analysis and to recognise and score the quality attributes that define the samples. A structured 9-point numeric scale[18] was employed to study the colour, flavour, consistency, swallowing and global acceptance attributes. The panellists tested ten different samples (five hydrocolloids, two consistencies) and the sensory analysis was carried out 24 h after preparing the texture-modified sauces, which were stored at 4 °C. Samples were presented to the panellists at 37 ºC in a plastic cup labelled with 3 arbitrary digits.

2.9 Statistical analysis

Results were statistically processed by the Statgraphics Centurion XVI software. The data were subjected to analysis of variance (ANOVA), and the means were compared using the Tukey-Kramer HSD test. Results marked with different letters are significantly different at $p<0.05$.

3. Results and Discussion

3.1 Colour and texture characterisation of samples

Colour is an important quality attribute in food industries, which influences consumer’s choice and preferences. Table 2 shows the colour variations (ΔE^*) of the texture-modified sauces compared to the unmodified sauce (control) at 25 ºC, 37 ºC and 55 ºC. Slightly differences were observed for all the samples, regardless of temperature, except for the CSM samples that presented lower luminosity (data not shown). Therefore, the highest colour differences (ΔE^*) were observed for those samples prepared with CSM, which exceed the just noticeable difference.[19] It could be attributed to the presence of natural pigments or tannic substances from the tegument of chia seeds.[20]

Texture is also an important factor in determining consumer acceptability of texture-modified products. Its analysis provides information on products structure and changes, following an applied force.[21] Table 2 summarises the texture parameters, maximum force related to the firmness and the area under the curve related to the consistency, of the different texture-modified sauces at 25 ºC, 37 ºC and 55 ºC. Although within the same consistency level the samples show similar apparent viscosity values, measured at 25 ºC with a shear rate of 50 s^{-1} (Table 1), significant differences ($p<0.05$) were noticed among sauces prepared with the target hydrocolloids. Moreover, greater area and maximum force values were observed when higher hydrocolloid concentrations are employed. For the honey-like consistency samples, the sauce prepared with CSM exhibited the highest area and maximum force values and, consequently, it had greater consistency and firmness. The lowest area and maximum force values were shown by samples containing CMC as texturing agent. In case of the pudding-like consistency samples, GG and CSM sauces exhibited the highest consistency and firmness. The GG macromolecule is a chain of (1→4)-linked β-D-mannopyranose units with single branching α-D-galactopyranose units connected to the mannose backbone through (1→6) glycosidic linkages. The extensive branching of GG is responsible for its excellent hydration properties and greater hydrogen-bonding activity.[22] Thus, the greater consistency and firmness observed could be explained by an intermolecular chain entanglement produced by the interaction of water molecules with the GG galactose chains.[23] On the other hand, CSM is an anionic water-soluble heteropolysaccharide which has been identified as a polymer of β-D-xylopyranosyl, α-D-glucopyranosyl and 4-O-methyl-α-D-glucopyranosyluronic acid.[24] The findings observed could be explained by the capacity of swollen CSM particles to act as fillers, which reduces the matrix mobility and increases products' consistency and firmness.[7]

Concerning the temperature effect, significantly lower ($p<0.05$) area and maximum force values were noted as temperature increased (Table 2). High temperatures could weaken the intermolecular chain entanglement of hydrocolloids, providing less consistent and firm products. This outcome was also observed by Arocas *et al.*[25] when evaluating the temperature effect on the extrusion properties of different starch sauces.

3.2 Flow and viscoelastic properties of samples

3.2.1 Flow rheological properties

Table 3 shows the results of the rheological parameters from the steady flow behaviour test of the different texture-modified sauces. The apparent viscosity of the samples, measured at 25 ºC with a shear rate of 50 s^{-1}, was close to 1350 mPa·s and 2400 mPa·s for honey-like and pudding-like consistencies, respectively. As expected, the higher the hydrocolloid concentration is, the greater the samples' viscosity. This is described by a power-type relationship and could be attributed to the higher total solids content, which produces higher viscosities due to an increased restriction in intermolecular motion caused by hydrodynamic forces and the formation of a hydrocolloid network.[26] Similar results were observed by Vieira *et al.*[1] when using increasing amounts of flax-seed gum as alternative thickener for dysphagic patients.

The flow behaviour index (n) was less than 1 in all the tested samples, which indicates the pseudoplastic behaviour of the sauces. The n values for the honey-like consistency samples were comprised between 0.304±0.014 and 0.459±0.013, whereas for the pudding-like consistency samples the n values ranged from 0.264±0.007 to 0.432±0.011. Products with $n < 1$ are favourable for a swallowing process with a reduced risk of aspiration, by giving the neuromuscular system a longer reflex response time to close the epiglottis.[27] Furthermore, as the texturing agent concentration increased the n values decreased probably due to breakdown of more overlapping and interpenetrated polysaccharide chains.[28] By analysing the n values among the texture-modified samples, it can be observed that the GG sauce had the lowest n value;

meanwhile the sample formulated with CMC and CSM exhibited the highest one. Talens *et al.*[5] reported similar n values in thickened pea creams designed for people with swallowing problems.

Regarding the consistency coefficient (K), the samples formulated with GG exhibited the highest K values being considered, therefore, the most consistent sauces. On the contrary, lower K values were noted in case of the CMC texture-modified sauce, being the latest results in accordance with those reported in the back extrusion test (section 3.1). The greater K values observed in case of GG samples could be ascribed to multiple intermolecular chain entanglements caused by the interaction of water molecules with the polymer chains.[23,24] Moreover, higher K values were noticed in samples presenting the pudding-like consistency. Thus, incorporation of greater amounts of hydrocolloids improved sauces consistency. It could be explained by a greater water binding capacity of hydrocolloids owing to an increase in the intermolecular interactions.[26] This outcome was also noticed by Talens *et al.*[5] while studying the flow rheological properties of thickened pea creams for dysphagic patients.

The temperature effect on the apparent viscosity at 50 s^{-1} of the texture-modified sauces was also investigated. As shown in Table 3, the apparent viscosity of samples decreased as temperature increased from 25 ºC to 55 ºC, indicating the temperature dependence of hydrocolloids. This may be attributed to the separation of the hydrocolloid molecules, which become greater at higher temperature, favouring the viscosity.[26] The Arrhenius model is commonly employed to describe the temperature-dependent behaviour of gums and mucilages.[29,30] Table 1 summarises the Arrhenius parameters of the different texture-modified samples. Non-significant ($p>0.05$) differences were observed for the Ea values between hydrocolloids' concentration. Among the samples, the CMC texture-modified sauce exhibited the highest Ea values, and the GG samples showed the lowest Ea values. Low Ea values indicates lower sensitivity to temperature changes, being the microstructure less prone to change.[26] According to Minjares-Fuentes *et al.*[30], it could be the result of high entanglement configurations.

3.2.2 Viscoelastic properties

To characterise the non-linear viscoelastic properties of the texture-modified samples and to determine the limits of the linear viscoelastic region (LVR) a stress sweep test was carried out. The study of the non-linear viscoelastic properties of texture-modified samples for dysphagic people is important since chewing and swallowing processes involve high deformations outside of the LVR.[4]

Figure 1 shows the changes in the elastic modulus (G') and viscous modulus (G") of samples, according to the stress, at 25 ºC, 37 ºC and 55 ºC. A predominant elastic behaviour (G' > G") was observed throughout the stress sweep applied, which is a common fact in weak viscoelastic systems. Once the LVR is passed, G' and G" values decreased as the stress increased, except for some samples. The sauces containing MS, GG and CSM showed a slight increase in the G" values, which lower again at higher stress levels. This behaviour is more evident for pudding-like consistency samples and at higher analysis temperature (37 ºC and 55 ºC). According to the classification of Hyun *et al.*[31] for diverse modulus behaviour in the non-LVR, it can be stated that TG and CMC samples exhibited a stress thinning behaviour, meanwhile those sauces containing MS, GG and CSM reflected weak stress-overshoot behaviour at the beginning of the non-LVR. Besides, the increase in G" values indicates higher energy amounts employed by the sauces during the deformation process. Microfractures in the gel structure of the texture-modified sauces can be originated. Consequently, the friction between the existent layers in the fracture site leads to energy losses in form of heat.[4] Similar results were observed by Sharma *et al.*[4] in texture-modified carrot purees with gellan gum, xanthan gum, pectin, carrageenan, and modified corn starch, and by Talens *et al.*[5] in texture-modified pea creams with xanthan gum, GG, konjac gum and TG, among others.

In general, as the temperature of samples increased, G' and G'' values slightly decreased. A similar trend was reported for flax seed gum–soy protein isolate dispersions.[32] Moreover, at the highest analysis temperature (55 ºC), the GG, TG and CSM pudding-like consistency sauces exhibited a stress hardening behaviour as the stress increased in the non-LVR, following the classification for diverse modulus behaviour.[31] In other words, the G' and G'' values of these sauces increased as the stress applied rose, but finally the samples flowed at 100 Pa. Stress hardening could be provoked by the formation of complex microstructures probably created due to stronger interactions among gums polysaccharide molecules.[31]

Table 4 presents the viscoelastic parameters, G'_{LVR}, $Stress_{LVR}$, and the flow point of the texture-modified sauces from the stress sweep test performed at 25 ºC, 37 ºC and 55 ºC. The G'_{LVR} value is related to the material stiffness.[5] Honey-like consistency samples manufactured with TG and CMC exhibited the lowest G'_{LVR} values at 25 ºC, 37 ºC and 55 ºC, being considered as products with low stiffness. On the contrary, the MS and GG sauces reflected a greater stiff structure, with significantly ($p<0.05$) higher G'_{LVR} values. Concerning the sauces with the pudding-like consistency, those samples prepared with TG and CMC reflected significantly ($p<0.05$) lower G'_{LVR} values and, consequently, low material stiffness, being more evident at 37 ºC and 55 ºC. Similar results were reported by Talens *et al.*[5] when investigating the material stiffness of pea creams thickened with CMC, TG and MS, among others. Furthermore, it is worth mentioning that sauces prepared with GG and CSM showed greater G'_{LVR} values as temperature rose probably due to the presence of hydrophobic interactions that get stronger with temperature. This could result in stronger interactions among hydrocolloids molecules.[34]

$Stress_{LVR}$ value is related to the structural stability of the product within the limits of the LVR.[5,10] Significant differences ($p<0.05$) were observed among the honey-like consistency samples. The sauces prepared with MS, GG, and CSM reflected the highest $Stress_{LVR}$ values, whereas those samples containing TG and CMC as texturing agents showed lower $Stress_{LVR}$

values, being more marked at 37 ºC and 55 ºC. Therefore, the sauces with MS, GG, and CSM presented better structural stability than samples containing TG and CMC. A similar behaviour was observed in the pudding-like consistency samples, but in that case, CSM sauces showed the best structural stability. The great structural stability of MS, GG, and CSM samples could lead to low brittleness products, probably reducing the formation of inhomogeneous boluses after the oral processing of samples. A scattered bolus could result in a variable flow rate during swallowing, increasing the risk in dysphagics as a consequence of the aspiration caused.[4] Moreover, significantly ($p<0.05$) higher $\text{Stress}_{\text{LVR}}$ values were observed for GG and CSM samples at 55 ºC than at 25 ºC and 37 ºC, probably due to presence of hydrophobic interactions that get stronger with temperature as above-mentioned.[33] The crossover point, where G'= G", is defined as the flow point. It provides information about the breakdown of the internal structure, resulting in the final flow.[35] The highest flow point values were exhibited by those sauces containing MS, GG and CSM, in spite of the consistency and analysis temperature. Thus, higher stress was required to provoke the internal structure breakdown of these samples, being greater when the hydrocolloids concentration increased (pudding-like consistency).

To characterise the linear viscoelastic properties of the texture-modified samples a SAOS test was performed. From this test and to better understand the dependency of G' and G" values on frequency and to evaluate the gel properties, ln G' and ln G" slopes (n' and n", respectively) *vs* ln frequency plot have been studied.[36] Moreover, the difference between the G'_0 and G''_0 values, at a frequency of 1 Hz, has been used as a measure of gel strength. Table 5 summarises the gel properties' parameters of the texture-modified sauces at 25 ºC, 37 ºC and 55 ºC. It can be observed that n' and n" values are comprised between 0 and 1, which could be ascribed to weak gels behaviour.[35] Significantly ($p<0.05$) lower n' values were noticed in case of samples manufactured with MS and GG as texturing agents, indicating lesser frequency-dependence; whereas the lowest n" values were recorded for those samples prepared with GG, regardless of the consistency and analysis temperature. When a greater hydrocolloid concentration was employed, the dependence of G' and G" on frequency was lower. This effect could be explained by the greater water binding capacity of hydrocolloids due to higher intermolecular interactions as their concentration rose. Talens *et al.*[5] also reported this outcome in pea creams thickened with ten different hydrocolloids.

Concerning the gel strength (G'_0 - G''_0), at both consistencies and within the same analysis temperature, the MS, GG and CSM sauces exhibited relatively high gel strength values, whereas the TG sample presented the lowest gel strength value. Higher gel strength values were observed when working at the highest analysis temperature, being especially patent for the CSM texture-modified sauce. According to Hosseini-Parvar *et al.*[34] it could be explained by the presence of hydrophobic interactions that get stronger with temperature, resulting in stronger interactions among polymers molecules.

Table 5 also shows the viscoelastic properties of samples obtained from the SAOS test. For comparison purposes, the storage modulus (G'), loss modulus (G"), complex modulus (|G*|) complex viscosity (|η*|) and loss tangent (Tan δ) values were considered at a frequency of 1 Hz. A predominant elastic behaviour (G' > G") was observed in this study, which is a common fact in weak viscoelastic systems. The complex modulus (|G*|) is a measure of the product stiffness and rigidity. [33] In general, formulations containing MS, GG, TG and CSM showed great product stiffness and rigidity, being more marked in case of CSM texture-modified sauces as the temperature increased. As above-mentioned, stronger interactions among polymers as the temperature rose could be associated to the presence of hydrophobic interactions.[34] It is also important to remark that, in general, higher amounts of hydrocolloids conferred significantly ($p<0.05$) greater stiffness and rigidity to the texture-modified sauces. This effect was more evident in case of CSM sauces. The use of larger amounts of polymers could increase product' stiffness and rigidity because of the robust network structure created.

The complex viscosity (|η*|) is a measure of total resistance to flow according to the angular frequency.[5] Generally, samples showing greater resistance to flow were those prepared with MS and GG, meanwhile the use of CMC as texturing agents diminished the resistance to flow of sauces. In regards to the analysis temperature, at 55 ºC, the GG and CSM texture-modified sample reflected the greatest resistance to flow, being this effect more marked in case of CSM at the pudding-like consistency probably due to greater intermolecular interactions originated. Tan δ provides information on the balance of the material's viscoelastic modulus.[4] Tan δ values below 0.1 indicate strong gels, Tan δ values between 0.1 and 1 denote weak gels, and Tan δ values above 1 are indicative of dilute solutions.[5,35] All the formulations had Tan δ values below 1, which reinforced the notion that elastic properties would prevail over viscous ones. Tan δ values in the range of 0.1-1 have been suggested as safe-swallowing in dysphagic patients.[8] Furthermore, Nyström *et al.*[37] proved that dysphagic patients perceived easier to swallow thinning fluids with increased elasticity. Thus, considering that products with high elasticity degree (lower Tan δ values), resistance to deformation (higher |G*| values), and structural stability (higher $\text{Stress}_{\text{LVR}}$ values) would be safer to swallow,[10] it could be state that MS, GG, and CSM samples would be more appropriate for dysphagic patients.

To determine the influence of temperature on the structural changes of samples, a temperature sweep test was performed from 20 ºC to 80 ºC as shown in Figure 2. For MS samples with the honey-like and pudding-like consistencies, G' and G'' values decreased during the whole range of temperatures evaluated. Contrarily, both G' and G'' values lowered between 20 ºC and 50 ºC with a turn toward higher values (60-65 ºC), increasing further at 80 ºC for GG, GT, CMC and CSM texture-modified sauces. As can be observed, this effect was more evident in case of GG, TG and CSM texture-modified sauces. Hosseini-Parvar *et al.*[34] and Tha Goh *et al.*[38] observed similar results in basil seed gum solutions and in chia seed polysaccharide dispersions, respectively, attributing this outcome to greater intermolecular interactions among hydrocolloids molecules, which took place at higher temperatures. Besides, Tan δ values were particularly variable for GG, TG, CMC and CSM. The GG and TG texture-modified sauces exhibited increasing Tan δ values until the high temperature zone (60 ºC - 80 ºC) were they sharply dropped. Nevertheless, CMC and CSM samples showed a constant decreased of their Tan δ values, until the high temperature zone were those values dropped drastically. These findings were more patent in case of samples with the pudding-like consistency. Furthermore, non-significant (*p>0.05*) differences were observed in Tan δ values for the MS texture-modified sauces over the temperature range studied. Despite the changes observed in Tan δ values of samples, it is worth mentioning that they were comprised between 0.1 and 1. Thus, all the products can be considered safe-swallowing for dysphagic patients at the range of temperatures evaluated.[9]

3.3 Simulated mastication assay

In this assay, the maximum peak force was taken as a measure of material consistency, the maximum negative force was taken as the material adhesiveness, and the apparent shear viscosity (at 10 s^{-1}) obtained during the fixed gap stage was related to the tongue sliding against the palate.[5,15]

For better comparison among samples, Figures 3 and 4 show the maximum positive and negative forces, and apparent viscosities of all the samples, in presence and absence of artificial saliva, for ten compression-shearing-decompression cycles. A slight decrease in the maximum and minimum force values was observed for all the samples in absence of artificial saliva from the first to second cycles, being more marked in case of CSM texture-modified sauces. It can be associated with the breakdown of the sauces' structure as explained by Chung *et al.*[15] All the CMC sauces exhibited the lowest consistency values over the study, whereas the GG and CSM samples presented the highest consistency values (Figure 3). These results fall in line with those perceived in the back extrusion test and flow rheological properties (sections 3.1 and 3.2.1). Nonetheless, in absence of saliva, non-significant ($p>0.05$) differences were observed for samples' adhesiveness.

With artificial saliva, the maximum and minimum force values significantly ($p<0.05$) decreased for both samples' consistencies mainly due to their dilution. Besides, this effect was greater in samples containing MS (Figure 3). As expected, the pancreatic α-amylase present in the saliva caused the degradation of this hydrocolloid mainly composed by modified starch. Indeed, CSM and TG texture-modified sauces exhibited scarcely greater adhesiveness than GG, CMC, and MS samples in presence of artificial saliva, which could be solved by same formula adjustments.

Concerning the apparent shear viscosity, in absence of artificial saliva, the samples containing GG and CMC as texturing agents exhibited the highest and lowest apparent viscosity values, respectively, regardless of the consistency level (Figure 4). On the contrary, when adding artificial saliva to the sauces, slightly higher apparent viscosity values were noted for the CSM samples, being this effect more evident for the pudding-like consistency. Thus, the greater tongue sliding against the palate was offered by CSM samples. Indeed, the lowest viscosity value was observed for the MS texture-modified sauces at both consistency levels, being considered, therefore, less appropriate than CSM or galactomannan gums for dysphagic patients. During food oral processing, products are blended with saliva, which contains α-amylase, responsible for the breakdown of starch components and viscosity reduction.[11] The decrease in viscosity can affect the risk of aspiration by the patient. Hence it is crucial to evaluate texture-modified products in terms of their resistance to a hydrolysis reaction with saliva for dysphagia management.[10,11]

3.4 Sensory evaluation

The sensory analysis is an essential tool for determining the acceptance of foods. The GG texture-modified sauces, at the honey-like consistency, showed the highest scores for colour, flavour and easy swallowing attributes (Figure 5). Significant differences ($p<0.05$) were observed among samples at honey-like and pudding-like consistencies. In case of the pudding-like consistency, the GG, MS, CMC sauces presented the greatest scores for colour, flavour, and easy swallowing attributes. Concerning the perceived consistency by panellists, TG, MS, and GG samples were noticed as the most consistent for the honey level, whereas CMC, MS, and GG sauces presented the highest scores for the pudding level. On the contrary, CSM sauces exhibited significantly ($p<0.05$) lower scores for colour, flavour, consistency, swallowing and global acceptance attributes than MS, GG, TG and CMC samples. Finally, it is noteworthy that the MS and GG texture-modified samples, at the honey-like and pudding-like consistencies respectively, presented the best global acceptance.

4. Conclusions

Texture-modified Spanish sauces present similar apparent viscosity values at 25 ºC and at a shear rate of 50 s^{-1}. Nevertheless, they exhibit different texture, flow, viscoelastic, masticatory, and sensory properties. The CMC samples show lower consistency, firmness, stiffness, and resistance to flow than MS, GG, TG and CSM samples, and are greatly affected by temperature changes. Saliva incorporation reduces the consistency, adhesiveness, and viscosity of all the samples. Therefore, due to their good elasticity degree, relatively high resistance to deformation and structural stability, and better resistance to the salivary α-amylase action, the GG and CSM texture-modified sauces would be more appropriate for dysphagic patients. However, the sensory analysis shows that the CSM texture-modified samples, at both consistency levels, presented the lowest scores for the tested attributes. This formula needs some adjustments to get good sauces from an organoleptic point of view.

The results of this work could provide valuable information for preparing and serving texture-modified sauces with desirable textural, rheological, viscoelastic, masticatory, and sensory properties for people with swallowing difficulties by using common gums or alternative texturing agents such as CSM. Nonetheless, further studies on the lubrication properties of dysphagia-oriented products prepared with CSM should be conducted by means of tribological tests, to fully understand the behaviour of texture-modified products during swallowing.

Authors Contributions

Susana Ribes: Methodology; Investigation; Data curation; Visualisation; Writing (original draft); Writing (review & editing); Raquel Estarriaga: Data curation; Investigation; Visualisation; Raúl Grau: Writing (review & editing); Project administration; Resources; Funding acquisition; Pau Talens: Conceptualisation; Methodology; Investigation; Supervision & Validation; Writing (review & editing); Project administration; Resources; Funding acquisition.

Acknowledgements

Authors thank to the “Ministerio Español de Ciencia e Innovación” for the financial support provided through the RTI2018-098842-B-I00 Project. Susana Ribes also thanks the Generalitat Valenciana for her Postdoctoral Fellowship (APOSTD/2020/264).

Declarations of interest

There are no conflicts to declare.

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Figure captions

Figure 1. Changes in elastic (G') and viscous (G'') modulus with the stress sweep test applied. Curves are representative runs. Modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM).

Figure 2. Temperature sweep of the different texture-modified sauces at honey-like and pudding-like consistencies from 20 ºC to 80 ºC. Curves are representative runs. Modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM).

Figure 3. Maximum positive (consistency) and negative forces (adhesiveness), in presence and absence of artificial saliva and at the honey-like and pudding-like consistencies, for 10 compression-shearing-decompression cycles. Values are the average of two independent experiments. Modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM).

Figure 4. Apparent viscosities changes of the texture-modified sauces, in presence and absence of artificial saliva and at the honey-like and pudding-like consistencies, for 10 compression-shearing-decompression cycles. Values are the average of two independent experiments. Modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM).

Figure 5. Average score of the attributes tested in texture-modified sauces with honey-like and pudding-like consistencies. *Indicates significant differences among samples ($p < 0.05$) (n = 34).

Modified starch (MS), guar gum (GG), tara gum (TG), sodium carboxymethylcellulose (CMC) and chia seed mucilage (CSM).

Table captions

Table 1. Concentration (%, w/w) of each hydrocolloid employed to prepare the texture-modified sauces, their apparent viscosities (mPa·s) measured at 25 ºC with a shear rate of 50 s^{-1}, and Arrhenius parameters of the different texture-modified samples.

Table 2. Colour variations compared to the unmodified sauce (ΔE*), and texture parameters at 25 ºC, 37 ºC and 55 ºC.

Table 3. Rheological parameters from the steady flow behaviour test at 25 ºC, 37 ºC and 55 ºC.

Table 4. Viscoelastic parameters obtained from the stress sweep test at 25 ºC, 37 ºC and 55 ºC.

Table 5. Gel properties parameters and viscoelastic properties, at a frequency of 1 Hz, obtained from SAOS test at 25 ºC, 37 ºC and 55 ºC.