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Whey protein concentrate gels with different sucrose content: instrumental texture measurements and sensory perception

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Abstract

Correlations between instrumental texture, sensory texture and sweetness perception were studied in whey protein concentrate (WPC) gels at different pH (4 and 7), sucrose (0-40%, w/w) and whey protein (10-20%, w/w) content. The presence of sucrose modified the structure of WPC gels, mainly at pH 4, making the gel structure more homogeneous and with smaller pores. Sucrose also increased the solid behaviour of gels, their water holding capacity, hardness and adhesiveness. Sweetness perception decreased as protein concentration increased, and was higher in gels at pH 4 than in gels at pH 7. A good correlation was obtained between the instrumental and sensory attributes hardness, cohesiveness and elasticity.

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1. Introduction

Food texture is a major criterion of food quality, since it influences consumer acceptance of foodstuffs (Szczesniak & Kahn, 1971). In many products, fats and sugars have long played an important role in texture. However, new health trends among consumers demand foods reduced in these components, but, needless to say, not reduced in taste or texture. Thus, the development of foodstuffs with low sugar and fat content, but with the same, or even better, sensory quality, has become a challenge for the food industry.

Whey protein concentrates (WPCs) contribute to enhance attributes such as creaminess, texture or water binding in different food systems (Johnson, 2000; Ohmes, Marshall, & Heymann, 1998).When whey protein (WP) gelation takes place under conditions of electrostatic repulsion between protein molecules, fine-stranded structures are obtained. On the other hand, at pH close to the isoelectric point, gels are opaque with a coarse particulate structure (Clark, Judge, Richards, Stubbs, & Sugget, 1981; Stading, Langton, & Hermansson, 1993). Moreover, the behaviour of WP is very different under acid conditions or at neutral pH. Non-covalent interactions (van der Waals attractive forces, hydrogen bonds and electrostatic and hydrophobic interactions) will determine the structure of gels at acid pH, while at neutral pH intermolecular sulphydryl-disulphide interchange reactions are favoured (Lupano, Dumay, & Cheftel, 1992; Shimada & Cheftel, 1988; Yamul & Lupano, 2003).

Protein concentration also plays a key role in gel formation. Different textures are obtained within the concentration range of 7% to 20% (w/w). At lower concentrations (<7%, w/w) the gel is not formed (Huffman, 1996, Tang, McCarthy, & Munro, 1995), and at concentrations above 20% (w/w) it is difficult to obtain a homogeneous dispersion suitable for gelation.

The microstructure of a gel, whether it is stranded or particulate, will directly influence its sensory perception. Stranded gels are springy and breakdown into large particles with minimal release of fluid during mastication. On the other hand, particulate gels release a detectable amount of fluid and break down into small particles that adhere to the teeth during chewing (Gwartney, Larick, & Foegeding, 2004). In addition, textural characteristics of food matrices influence the perception process by facilitating (or not) the release of tastants, their mixing with saliva and their interaction with gustatory receptors. In a fluid matrix, tastants are immediately mixed with saliva and reach the gustatory receptors quickly (Bayarri, Rivas, Izquierdo, & Costell, 2007). In contrast, in semi-solid foods, such as WP gels, they are released at different rates depending on the interactions with the gel and the chewing process, i.e., the breakdown rate.

It is for this reason that several authors have attempted to correlate sweetness with texture in liquid and solid foods. Lethuaut, Brossard, Rousseau, Bousseau, and Genot (2003) studied the effect of sucrose on the sweetness-texture interactions in carrageenan gels. DeMars and Ziegler (2001) and Moritaka and Natio (2002) found that sweetness in gelatin gels decreased as gelatin content increased. Holm, Wendin, and Hermansson (2009) investigated the hardness of pectin gels on the sweetness perception. Bayarri et al. (2007) studied the sweetness perception in carrageenan and guar gum gels. All these studies agree that the harder the gels, the lower the sweetness perception.

In addition, numerous authors have studied the combination of sucrose–WP gel (Boye, Kalab, Alli, & Ma, 2000; Dierckx & Huyghebaert, 2002; Kulmyrzaev, Bryant, & McClements, 2000a); however, the core of their research was focused on the physicochemical properties without considering the sensory texture perception. The aim of this work was to study the correlations between instrumental and sensory texture in WPC gels at different pH levels, sucrose and WP content. Results could be useful in determining the best condition to create a low sugar content product with an attractive texture having the advantage of the nutritional and functional properties of WP.

2. Materials and methods

2.1. Gel preparation

WPC was a gift from Arla Foods Ingredients S.A. (Martinez, Buenos Aires, Argentina). WPC contained 77.71% (w/w) protein (N × 6.38), 5.74% (w/w) moisture, 2.77% (w/w) ash, 3.83% (w/w) lipids and 9.95% (w/w) lactose (estimated by difference). Commercial sucrose (Ledesma, Ingenio Ledesma SA, Jujuy, Argentina) was also used. All chemicals employed were of analytical grade. Gels were prepared according to the technique described in previous reports (Cassiani, Yamul, Conforti, Pérez, & Lupano, 2011; Yamul & Lupano, 2003, 2005). A completely randomised factorial design was obtained using the Statgraphics plus 5.1 software (StatPoint Inc., USA). The three factors were: pH, WP concentration and sucrose concentration. The levels of the factors were incorporated into the design and were analysed in 30 combinations. For gel composition and pH see Table 1.

2.2. Instrumental evaluation

Confocal laser scanning microscopy was carried out as described by Cassiani et al. (2011). The following samples were assayed: sucrose content, 0%, 20% and 40% (w/w); pH of gels, pH 4 and pH 7; protein content of all gels, 10% (w/w).

Large deformation measurements were carried out as described in previous works (Cassiani et al., 2011; Yamul, & Lupano, 2003, 2005), except for the hardness and Young's modulus that were obtained by compressing the sample down to 20% of the original height. Sample hardness was defined as the height of the peak of the force versus time/deformation curve and the Young's modulus was calculated from the initial slope (linear region) of the same curve. The average (± standard deviation) of at least three determinations was calculated for each type of sample.

Water holding capacity (WHC) was performed as described in previous works (Cassiani et al., 2011; Yamul & Lupano, 2003, 2005). WHC was expressed as a percentage of the initial water remaining in the gel after centrifugation. Values are the average (± standard deviation) of at least two determinations.

2.3. Sensory evaluation

2.3.1. Sorting task

A panel of 16 assessors, namely female students from Facultad de Ciencias Agrarias, Pontificia Universidad Católica, Argentina; 20–24 years old, analysed the samples in duplicate in two sessions by applying sorting task with description (Lelievre, Chollet, Abdi, & Valentin, 2008). Assessors were highly familiar with discrimination testing and were trained in descriptive methods in the evaluated samples. Testing took place in individual booths kept at 22 ± 2 °C, under daylight (6,500 K). Ten grams of sample were placed in three digit coded cups and presented in random order. Mineral water was provided for oral rinsing between samples. Assessors were allowed to taste as many samples as they wished and in any order; they were free to make as many groups as they wanted. Finally, they were asked to describe each group of samples by using the attribute definitions shown in Table 2 and/or any other concept they wanted.

2.3.2. Sweetness intensity quantification

A panel of 14 assessors, who participated in such sorting task, was trained to quantify the sweetness intensity of the samples in duplicate. First, they ordered the samples for sweetness intensity having two sucrose solutions (5 and 15%, w/w) as standards. Once the samples were ordered, assessors measured sweetness levels on a 15 cm line scale.

2.3.3. Texture profile

The same panel of 14 assessors analysed the texture of the selected samples by following Quantitative Descriptive Analysis (QDA) method (Stone & Sidel, 1993). They received three training sessions (one-hour long each), during which, with the aid of standards, they learnt how to measure the attributes listed in Table 2. The QDA was done in duplicate during two other sessions, under the same conditions as used in the sorting task (above).

2.4. Data analysis

Statistical analysis was carried out using PASW Statistics 18 software (SPSS Inc. Chicago, IL, USA). To estimate the influence of the factors pH, sucrose and protein concentration on the gel instrumental texture, an analysis of variance (ANOVA) of the data was performed. Means comparison was carried out with the least significant differences (LSD) calculated with the Fisher test at a level of 95%. Sorting task data were analysed by applying multidimensional scaling method. Analysis of variance (ANOVA) was carried out to assess sensory attributes significantly different among samples. The variability of each descriptor was studied using a model where the assessor was considered a random factor and sample and replication fixed factors. Multiple means comparisons were carried out by

Student Newman-Keuls (SNK) test at $P < 0.05$. Principal Component Analysis (PCA) was conducted to examine the relationship among sensory attributes and samples, correlation matrix was used and the minimum eigenvalue was set at 1. Clusters were performed by K-Means command. Pearson's Correlation was used to explore relationships between sensory and instrumental data.

3. Results and discussion

3.1. Microstructure of the gels.

The confocal microscopy images of gels can be seen in Fig. 1. The clear areas correspond to the fluorescence of rhodamine B, revealing the presence of a network of WP. The dark areas correspond to water zones. The gels prepared at pH 7 (Fig. 1d,e,f) presented a homogeneous distribution of fluorescence dots, whereas the gels prepared at pH 4 (Fig. 1a,b,c) exhibited a structure of WP aggregates with big pores. Yamul and Lupano (2003) observed that when gelation took place at a pH close to the isoelectric point of WP a coarse particulate structure was obtained due to the decrease of the electrostatic repulsion. The isoelectric pH of β-lactoglobulin (the main WP) is 4.6, explaining the differences in the structure between pH 7 and pH 4 gels (Fig. 1). Moreover, Boye et al. (2000) found that, in general, the size of the protein clusters and the void spaces within the gel matrix tended to decrease as the pH changed from acid to basic. At alkaline pH proteins are generally more unfolded, exposing more reactive sites for crosslinking, and therefore enhances gel network formation (Boye et al., 2000).

The concentration of sucrose modified the structure mainly of acid gels (Fig. 1). The gel structure became more homogeneous and pores became smaller as sucrose content increased. Similar results were obtained in other systems, such as micellar casein gels (Schorsch, Jones, & Norton, 2002) and WPC gels with honey (Yamul & Lupano, 2003). This could be explained by taking into account that sucrose increased the attraction between WP molecules through hydrophobic interactions (Baier & McClements, 2001; Kim, Decker, & McClements, 2003; Kulmyrzaev et al., 2000a; Kulmyrzaev, Cancelliere, & McClements, 2000b). Neutral gels already presented an homogenous structure before the addition of sucrose; thus, only a slight change in the gel microstructure was observed (Fig. 1).

3.2. Textural properties.

Fig. 2 shows the texture properties of WPC gels with different content of sucrose and WP prepared at pH 4 and pH 7. As WP content increased, an increase in the hardness, Young modulus, elasticity and cohesiveness of the gels was observed. The increase in these parameters can be explained by an increase in the level of cross-linking between the molecules as WP content increases. Acid gels were more adhesive and less cohesive than pH 7 gels, especially at high sucrose content and at 10% (w/w) WP. Cohesiveness is a function of the energy that holds molecules together in the gel structure. Sulphydryl-disulphide interchange reactions are favoured in neutral gels, which could explain their higher cohesiveness.

Sucrose slightly decreased the elasticity of gels at any conditions assayed (Fig. 2) but increased hardness, Young's modulus, cohesiveness and adhesiveness of WPC gels. On the other hand, sucrose increased the adhesiveness of gels due to its ability to form hydrogen bonds, especially in acid gels. Neutral gels were more cohesive and, thus, would have less ability to adhere to the metal of the probe.

3.3. Water holding capacity.

Fig. 3 depicts the WHC of WPC gels as a function of sucrose and WP content. Significant differences (*P* <0.001, Table 3) were observed in WHC at different sucrose content at both pH values studied, reaching similar values at high sucrose concentration. On the other hand, protein content did not modify significantly the WHC of gels (*P* > 0.05; Table 3). Acid gels exhibited an aggregated structure with big pores (Fig. 1a,b,c); thus, the flux of water in acid gels would be easier than in neutral gels, explaining their lower WHC. Similar results were obtained by Verheul and Roefs (1998) with WP gels prepared with different contents of NaCl. On the other hand, at pH 7, gels exhibit high WHC; thus, it is expected that the energy dissipation in the viscous modulus due to the flow of liquid through a matrix will be low, and gels would behave primarily elastic.

Hydrogen bonds between small molecules significantly increase the viscosity of a liquid, and the bonds are weak enough to be temporarily extended, exchanged or broken (Pomeranz, 1978). Sucrose has the possibility to form hydrogen bonds with water molecules and, thus, increased the viscosity of the solution trapped within the gels pores. As sucrose content increases the viscosity of the solution also increased and the liquid flux through the matrix decreased, explaining the high water-holding capacity of gels containing sucrose (Fig. 3).

3.4. Sensory analysis

3.4.1. Sample selection.

Samples for sensory analysis were selected based on the results of the instrumental analysis, keeping only samples with a sucrose concentration of 10, 20 and 40% (w/w).

Samples without sucrose (0%, w/w) were not considered because they were not significantly different ($P > 0.05$) from those with 10% (w/w) of sucrose in many of the conditions assayed, and also due to the potential off-flavour of the WPC gels without sucrose that can derive from the variable amounts of residual lactose and 3–7% (w/w) lipid materials that are susceptible to chemical reactions (Morr & Ha, 1991).

All samples with 30% (w/w) sucrose and 15% (w/w) protein were also discarded because they were not significantly different ($P > 0.05$) from the next corresponding concentrations in almost all conditions assayed.

3.4.2. Sorting task

Sorting task results are presented in Fig. 4. According to this analysis, two major groups of samples were formed, based mainly on protein concentration. On the one hand, samples containing 10% (w/w) protein (samples 2, 3, 5, 17, 18 and 20) could be characterised by the attributes creamy, wet surface, smooth, bright, humidity, soft and cohesive. On the other side, samples containing 20% (w/w) protein (samples 12, 13, 15, 27, 28 and 30 were described as dry, fracturable, hard and rough.

Within each group certain samples were too close or even superimposed, showing that no differences were found (Fig. 4). This was the case for samples 2, 3 and 5 (pH 4, 10% protein, 10, 20 and 40% sucrose respectively) and sample 17 and 18 (pH 7, 10% protein, 10 and 20% sucrose respectively) in the first group and samples 13 and 15 (pH 4, 20% protein, 20 and 40% sucrose respectively) and samples 27 and 28 (pH 7, 20% protein, 10 and 20% sucrose, respectively) in the second group. Therefore, to analyse by QDA only those samples perceived as different, samples 3, 18, 13 and 28, which also had an intermediate sugar concentration (20%, w/w), were discarded.

3.4.3. Texture profile and sweetness quantification

An ANOVA of the mixed model for all sensory quantified attribute scores was performed to evaluate sensory panel performance and differences among samples (Table 3). It was found that the sources of variation were samples (P <0.001), and assessors only for hardness and moistness (P <0.05), indicating that the panel had a good performance for quantifying attributes, replicating responses and discriminating among samples. Moreover, the effect of protein content, pH and sucrose was studied on both sensory perception and instrumental measurements; this is also shown in Table 3.

pH and protein were the main factors that affected sensory and instrumental texture measurements (P <0.001), except for WHC, for which it was sucrose content that was the factor that most influenced WHC of gels. Although sucrose had a strong effect (P <0.001) on instrumental hardness, it was not reflected on sensory hardness; probably, the measured differences were within the differential threshold so they were not perceived by the assessors.

Mean values of all evaluated attributes for each sample are presented in Table 4. In terms of sweetness no significant differences were perceived between two couples of samples: samples 15 and 20 (both 40% sucrose; pH 4 + 20% protein and pH 7+ 10% protein, respectively) and 17 with 28 (both pH 7; 10% protein +10% sucrose and 20% protein + 20% sucrose, respectively).

In all cases, as sucrose concentration increased, sweetness perception also increased. However, at a same sucrose concentration, sweetness perception was smaller as protein concentration increased and this reduction was more important at pH 7. This is probably related to the fact that gels with a higher amount of protein prepared at neutral pH had a harder texture (Fig. 2b), which might decrease mass transfer, reducing the sucrose access to taste receptors. Moreover, as said before, sucrose favours interactions between protein molecules reducing the contact with the surrounding solution.

Literature shows that in gels derived from carrageenan, gellan, pectin and/or gelatin (Bayarri, Duran, & Costell, 2003; Boland, Delahunty, & van Ruth, 2006; Costell, Peyrolon, & Duran, 2000; Guichard, Issanchou, Descourvieres, & Etievant, 1999; Lundgren et al., 1986) perception of sweetness decreased with increasing hardness. Moreover, as a general rule, it is known that the higher the hydrocolloid concentration, the lower the perceived sweetness intensity (Bayarri et al. 2007).

To better interpret the data obtained from the textural profile, a PCA was carried out with the mean values obtained for each sample; the biplot of Principal Component 1 (PC1) versus Principal Component 2 (PC2) is presented in Fig. 5. This analysis explained 94% of the variance among samples with the first two components. The main attributes composing PC1 were hardness, roughness and cohesiveness, together with moistness and creaminess, which were opposite to the aforementioned. PC2 was positively defined by adhesiveness of mass, adhesiveness to teeth and thickness.

It can be seen that samples 27 and 30 (both pH 7 and 20 %, w/w, protein, 10 and 40%, w/w, sucrose, respectively) were grouped and described mostly by the attributes hardness, roughness, elasticity and cohesiveness (Fig. 5); samples 17 and 20 (both pH 7 and 10% protein, 10 and 40% sucrose, respectively) were mainly characterised according to moistness; samples 12 and 15 (both pH 4 and 20% protein; 10 and 40% sucrose, respectively) according to adhesiveness of mass and to teeth together with thickness and finally samples 2 and 5 (both pH 4 and 10% protein; 10 and 40% sucrose, respectively) were the creamiest. This confirmed results showed in Table 3, that sucrose was the least important factor influencing perceived texture in comparison to pH and protein concentration.

3.4.4. Instrumental and sensory correlation

To compare instrumental and sensory information, a Pearson's Correlation was done; the results are shown in Table 5. A high positive correlation was found between the instrumental and sensory attributes hardness ($P < 0.01$), cohesiveness ($P < 0.01$) and elasticity ($P < 0.001$), showing that the measured property was the same by both techniques. Instrumental hardness also correlated with the sensory attributes roughness ($P < 0.01$), cohesiveness ($P < 0.01$) and in a lower proportion with elasticity ($P < 0.05$). Probably, surface tactile information such as roughness (see Table 2 for definition) could also contribute to hardness perception. Even if sensory adhesiveness (adhesiveness of mass and adhesiveness to teeth) did not significantly correlate with the instrumental measurement of adhesiveness, the instrumental measurement of adhesiveness correlated with perceived creaminess and sweetness ($P < 0.05$). It must be taken into account that sucrose increased the adhesiveness and the sweetness of samples; thus, the correlation between the instrumental measurement of adhesiveness and the perceived sweetness could be due to the fact that all these attributes increased with sucrose content. Creaminess can be associated with the low elasticity of the samples, which decreased when sucrose content increased.

4. Conclusions

The presence of sucrose modified the structure of WPC gels mainly at acid pH, making the gel structure more homogeneous and with smaller pores. Sucrose also increased the solid behaviour of gels, their WHC, hardness and adhesiveness. An increase in the sucrose content higher than 10 % (w/w) was needed to perceive changes in sweetness in WPC gels at neutral or acidic pH. Sweetness perception decreased as protein concentration increases. Also, sweetness of gels prepared at pH 4 was higher than sweetness of gels

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prepared at neutral pH, indicating that texture is more important than the acid taste caused by pH in the perception of the sweetness of these gels. The instrumental and sensory attributes hardness, cohesiveness and elasticity showed a good correlation, indicating that the measured property was the same by both techniques. This information could be useful for the food industry since sensory evaluation by a trained panel is cost and time demanding.

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Table 1

Composition of acid and neutral WPC gels as function of protein and sucrose content.

Samples	Protein (%, w/w)	Sucrose (%, w/w) [a]	pH
1, 2, 3, 4, 5	10	0, 10, 20, 30, 40	4
6, 7, 8, 9, 10	15	0, 10, 20, 30, 40	4
11, 12, 13, 14, 15	20	0, 10, 20, 30, 40	4
16, 17, 18, 19, 20	10	0, 10, 20, 30, 40	7
21, 22, 23, 24, 25	15	0, 10, 20, 30, 40	7
26, 27, 28, 29, 30	20	0, 10, 20, 30, 40	7

[a] Values are respective to the sample number.

Table 2

Sensory attribute definitions, sample manipulation procedures and references chosen.

Attribute	Definition	References
Sweetness	Taste associated to a sucrose solution.	Sucrose solutions at 5 and 15%
Hardness	Force required to cut completely through the sample when placed between incisive teeth	(-) extreme: cream cheese Middle scale: olives, hotdogs (+) extreme: hard candy
Roughness	Degree of abrasion given by the surface of the product perceived on the lips and tongue.	(-) extreme: gelatin (+) extreme: cereal bar.
Moistness	Perception of water content released by the surface of the product. It was measured with the sample in the mouth, over the tongue and lips	
Elasticity-springiness	Degree or rate at which the sample returns to its original size-shape after partial compression between the tongue and palate.	(+) extreme: marshmallow
Cohesiveness	Degree to which sample holds together as a mass.	(+) chewing gum
Firmness	Resistance of the sample to movement or flow. It was measured as the force required to move the sample along the palate using the tongue.	
Adhesiveness of mass	Degree to which mass sticks to the palate or teeth (not sticky – very sticky).	
Adhesiveness to teeth	Amount of product which sticks to the teeth after mastication.	
Creaminess	Soft texture, velvety, smooth feeling which disappears when the mouth is rinsed	

Table 3

Analysis of variance results showing sensory panel performance, differences among samples and effect of protein, pH and sucrose on evaluated sensory and instrumental attributes.

Attribute	F-values [a]					
	Sample	Assessor	Replication	pH	Protein	Sucrose
Sensory						
Sweetness	1072***	0.6	0.16	1889***	1264***	9577***
Hardness	794***	2.2*	2.50	365***	5377***	0.4ns
Roughness	1137***	0.8	0.22	118***	5085***	232***
Moistness	2031***	2.5*	0.29	100***	13374***	10.3**
Elasticity	502***	1.2	0.14	2905***	1203***	4.8*
Cohesiveness	1389***	0.9	0.001	3092***	1897***	8.0*
Firmness	302***	0.9	0.32	449***	2113***	23.9***
Adhesiveness mass	890***	1.4	1.32	5482***	162**	356***
Adhesiveness teeth	354***	0.9	3.66	814***	2135***	185***
Creaminess	790***	1.4	0.28	3041***	2572***	41.7***
Instrumental						
Hardness				65***	187***	122***
Elasticity				143***	22***	2.5 ns
Young's modulus (*E*)				1228***	414***	304***
Adhesiveness				46***	134***	46***
Cohesiveness				138***	35***	8.3*
WHC				3.5 ns	1 ns	57.4***

[a] Significance values are: $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$; ns, not significant.

Table 4

Mean values for sensory attributes.

Attribute	Sample number [a]							
	2	5	12	15	17	20	27	30
Sweetness	48.2± 3.9[a]	143.8± 10.5[c]	42.4± 4.0[d]	114.6± 10.3[f]	26.9± 2.2[g]	117.5± 9.7[f]	6.8± 0.4[i]	59.6± 4.4[j]
Hardness	17.1± 2.2[a]	19.7± 2.8[a]	85.3± 5.0[b]	66.9± 7.8[c]	7.0± 0.3[d]	28.9± 2.9[e]	119.3± 15.8[f]	115.9± 12.6[f]
Roughness	17.8± 1.8[a]	22.0± 2.9[b]	95.4±10.5[c]	99.8± 11.9[d]	21.9± 3.5[b]	30.5± 3.4[e]	89.7± 8.3[f]	144.4± 10.3[g]
Moistness	114.8± 8.7[a]	100.7± 6.3[b]	38.5± 2.8 [c]	57.6± 5.7[c]	141.3± 4.4[d]	109.7± 5.7[e]	6.5± 0.7[f]	24.1± 2.4[g]
Elasticity	16.7± 2.8[a]	22.7± 3.0[b]	50.0± 5.8[c]	46.8± 4.0[d]	64.3± 4.3[e]	63.9± 6.1[e]	96.1± 10.6[f]	86.9± 7.8[g]
Cohesiveness	9.4± 2.2[a]	10.3± 1.4[a]	59.9± 6.0[b]	37.4± 3.2[c]	70.4± 6.3[d]	57.1± 5.6[b]	123.7± 12.4[e]	144.5± 10.9[f]
Firmness	37.8 ± 9.5[a]	47.9± 8.0[b]	118.8± 11.4[c]	85.8± 5.0[d]	7.5± 0.5[e]	39.6± 7.1[a]	65.4± 5.1[f]	78.6± 8.6[g]
Adhesiveness of mass	64.8 ± 5.0[a]	73.2± 6.0[b]	116.1± 6.6[c]	118.1± 12.0[d]	19.9± 3.2[e]	60.0± 6.8[f]	7.1± 0.3[g]	21.8± 2.6[e]
Adhesiveness to teeth	61.9± 5.2[a]	65.6± 5.9[a]	97.5± 8.4[b]	120.4± 16.0[c]	6.9± 0.3[d]	31.2± 4.3[e]	77.8± 6.9[f]	92.3± 9.4[g]
Creaminess	140.6± 14.1[a]	129.1± 12.1[b]	74.1± 6.8[c]	74.0± 4.3[c]	55.0± 3.7[d]	83.4± 9.0[e]	6.9± 0.3[f]	19.6± 2.6[g]

[a] See Table 1 for sample composition. Different superscript letters within each row indicate significant differences among samples according to Student Newman-Keuls (SNK).

Table 5

Pearson's correlation between instrumental and sensory parameters

Instrumental parameter	Sensory parameter [a]									
	Hardness	Roughness	Moistness	Elasticity	Adhesiveness mass	Adhesiveness teeth	Cohesiveness	Firmness	Creaminess	Sweetness
Elasticity	0.539	0.476	-0.381	0.946***	-0.750*	-0.154	0.913**	-0.109	-0.891**	-0.356
Adhesiveness	-0.704	-0.659	0.614	-0.707*	0.185	-0.268	-0.717*	-0.451	0.760*	0.730*
Cohesiveness	0.647	0.595	-0.498	0.914**	-0.692	-0.014	0.944**	0.045	-0.851**	-0.312
WHC	0.218	0.306	-0.205	0.282	-0.038	0.207	0.223	0.069	-0.236	0.668
Hardness	0.836**	0.888**	-0.738*	0.790*	-0.333	0.458	0.862**	0.418	-0.826*	-0.183
Young's modulus	0.620	0.629	-0.486	0.897**	-0.501	0.066	0.866**	0.118	-0.848**	-0.107
Sweetness	-0.374	-0.213	0.290	-0.485	0.508	0.120	-0.540	-0.008	0.538	1.000

[a] Significance values are: $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

Figure captions

Fig. 1. Microstructure of WPC gels with different amounts of sucrose observed by confocal laser scanning microscopy. Sucrose content: panels a and d, 0% (w/w); panels b and e, 20% (w/w); panels c and f, 40% (w/w). pH of gels: panels a, b, and c, pH 4; panels d, e, and f, pH 7. Protein content of all gels was 10%, w/w.

Fig. 2. Hardness, Young's modulus, springiness, adhesiveness and cohesiveness of WPC gels as a function of sucrose content. Protein content of gels: ■, 10% (w/w); ●, 15% (w/w); ▲, 20% (w/w). Panels a, c, e, g, and i are pH 4; panels b, d, f, h, and j are pH 7; bars show standard deviation. Values in the same graph with a letter in common are not significantly different ($P > 0.05$).

Fig. 3. Water holding capacity of WPC gels as a function of sucrose and WP content: ■, 10% (w/w/) WP; 15% (w/w/) WP; ■, 20% (w/w/) WP; ■. Panel a, pH 4; panel b, pH 7. See Table 1 for sample composition; bars show standard deviation.

Fig. 4. Sorting task representation of the evaluated samples; see Table 1 for sample composition.

Fig. 5. Principal component analysis of the sensory texture profile; see Table 1 for sample composition.

Figure 1

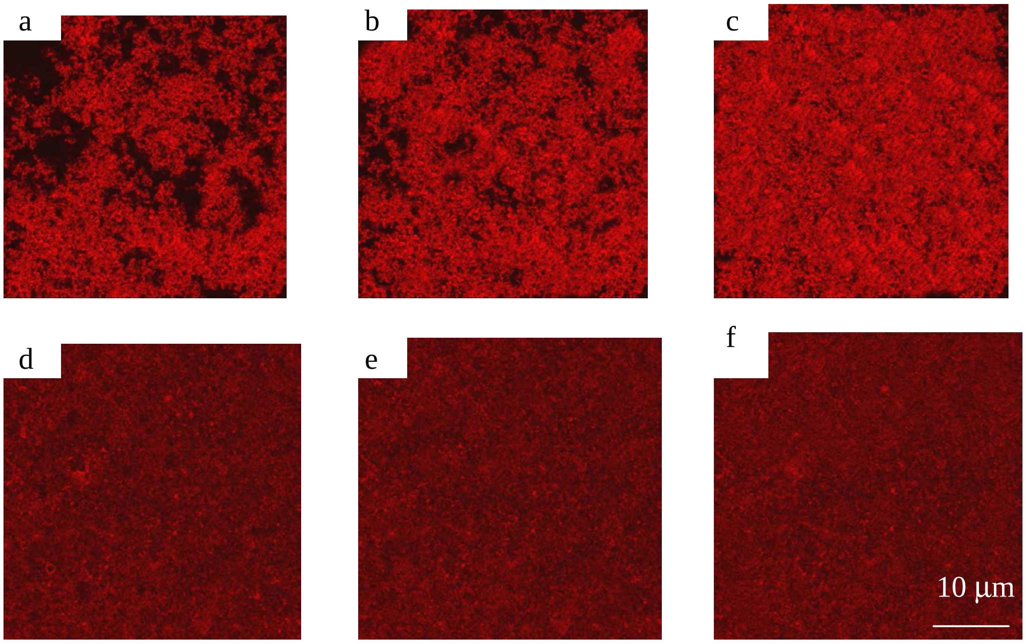


Figure 2

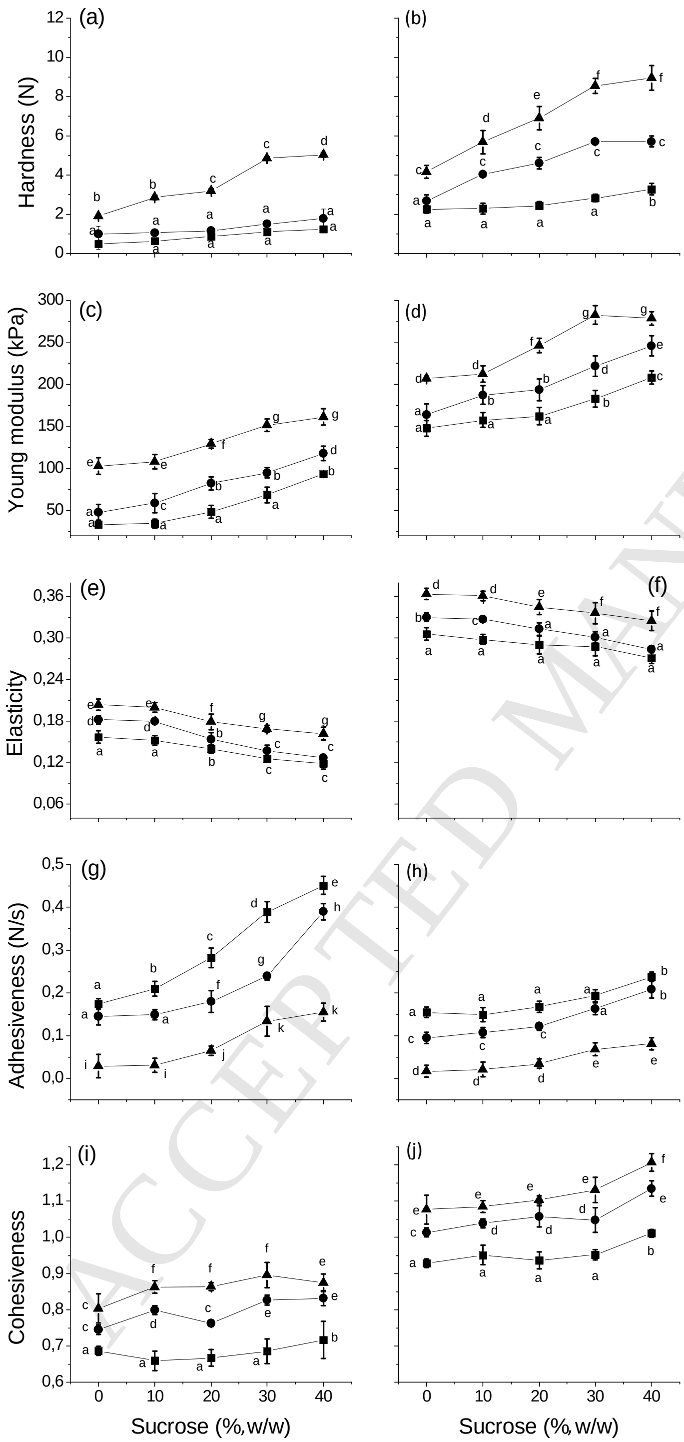

(a)
(b)
Hardness (N)
0
2
4
6
8
10
12
(c)
(d)
Young modulus (kPa)
50
100
150
200
250
300
(e)
(f)
Elasticity
0,06
0,12
0,18
0,24
0,30
0,36
(g)
(h)
Adhesiveness (N/s)
0,0
0,1
0,2
0,3
0,4
0,5
(i)
(j)
Cohesiveness
0,6
0,7
0,8
0,9
1,0
1,1
1,2
0
10
20
30
40
Sucrose (%,w/w)
Sucrose (%,w/w)

Figure 3

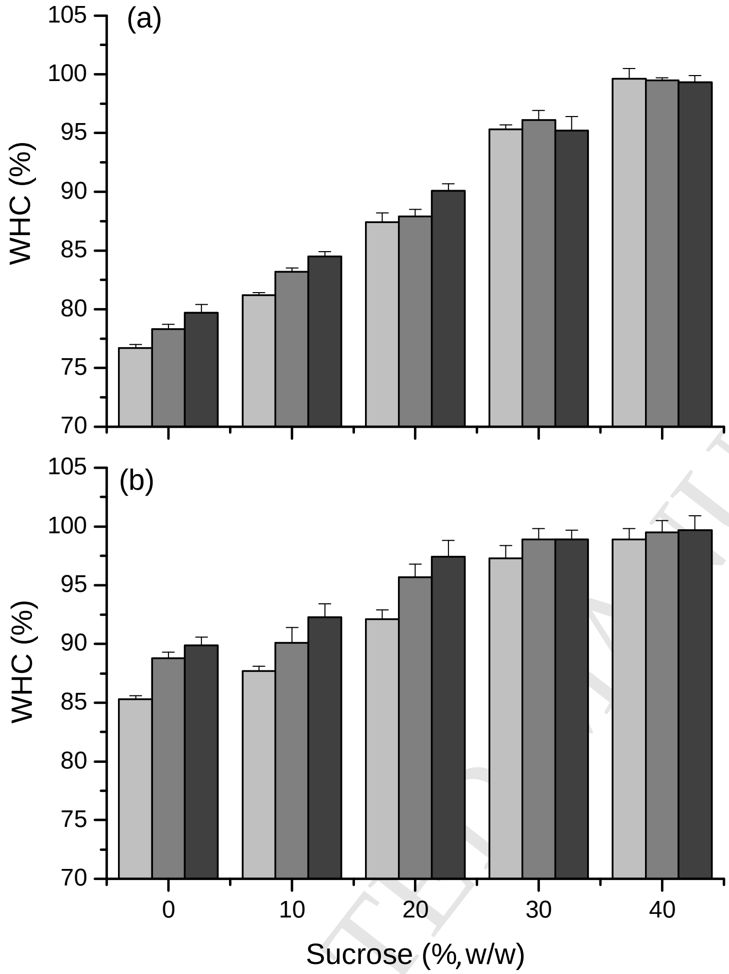

(a)
WHC (%)
105
100
95
90
85
80
75
70
(b)
WHC (%)
105
100
95
90
85
80
75
70
0
10
20
30
40
Sucrose (%, w/w)

Figure 4

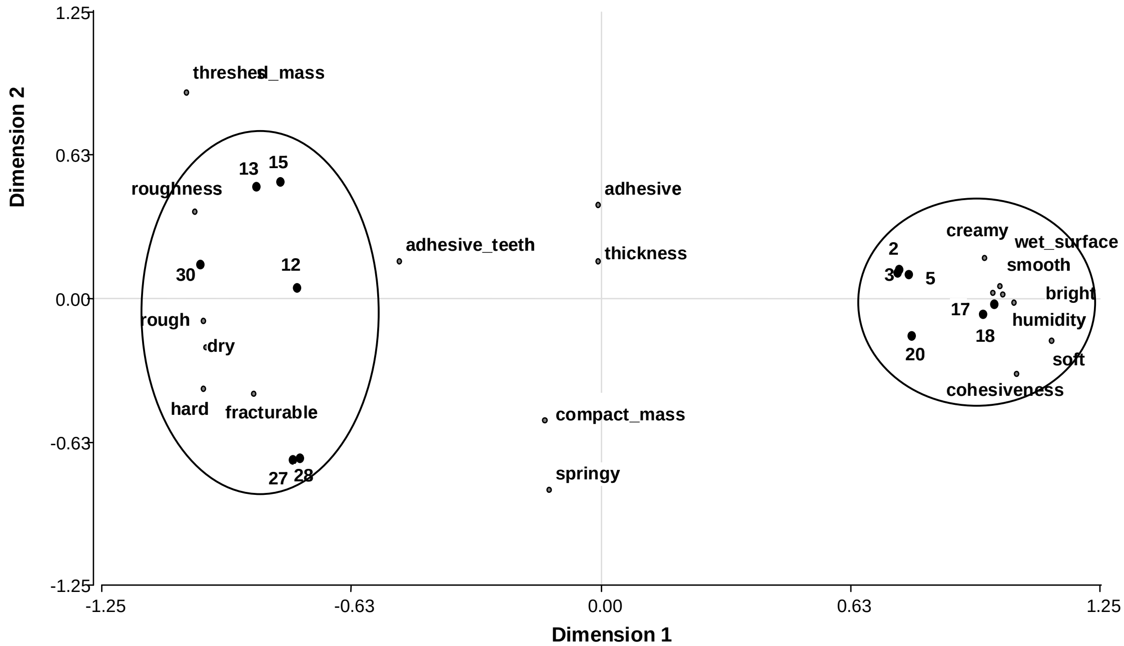
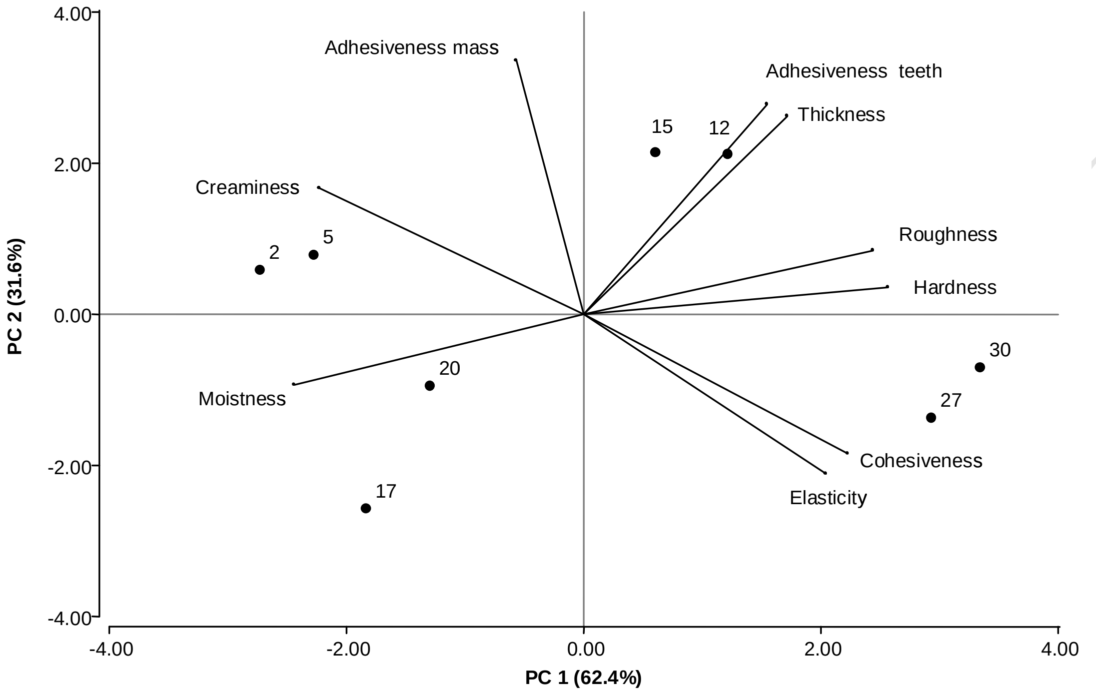

threshed_mass
roughness
13
15
adhesive
adhesive_teeth
thickness
creamy
wet_surface
smooth
2
3
5
bright
17
humidity
18
20
soft
cohesiveness
30
12
rough
dry
hard
fracturable
compact_mass
springy
27
28
1.25
0.63
0.00
-0.63
-1.25
Dimension 2
Dimension 1

Figure 5



4.00
2.00
0.00
-2.00
-4.00
PC 2 (31.6%)
-4.00
-2.00
0.00
2.00
4.00
PC 1 (62.4%)
Adhesiveness mass
Adhesiveness teeth
Thickness
Creaminess
Roughness
Hardness
Moistness
Cohesiveness
Elasticity
15
12
2
5
20
17
30
27