Food ©2011 Global Science Books

Flow Behaviour and Sensory Properties of Extra Virgin Olive Oil-Enriched Mashed Potatoes: Influence of Cryoprotectants and Freezing

María Dolores Alvarez* • **Cristina Fernández** • **Wenceslao Canet**

Dept. of Characterization, Quality and Food Safety, Institute of Food Science, Technology and Nutrition (ICTAN)-CSIC, José Antonio Novais no 10, E-28040 Madrid, Spain

Corresponding author: * **mayoyes@ictan.csic.es**

ABSTRACT

Extra virgin olive oil (EVOO) has interesting nutritional characteristics, which are linked to its biophenols content with very important antioxidant properties. The aims of this work were to investigate the effect of the addition of EVOO at four concentrations (0, 10, 25 and 50 g kg^{-1}) on flow behaviour and sensory attributes of fresh and frozen/thawed mashed potatoes (FMP and F/TMP respectively) formulated with and without added cryoprotectants (kappa-carrageenan (κ-C) and xanthan gum (XG) (each cryoprotectant at 1.5 g kg^{-1}). Other steady shear and yield stress data, colour, expressible water (E_w) and overall acceptability (OA) were also examined. All the samples displayed shear-thinning flow behaviour. Results showed that between the factors under consideration, EVOO concentration was the factor that set the minor difference among the most of the rheological properties, whereas the addition of κ-C + XG resulted in main differences between mashed potatoes (MP). However, EVOO concentration set the major difference among the OA of the samples. Increase of EVOO content produced softer systems due to increasing droplet concentration, whereas addition of cryoprotectants led to more structured systems related to the gelling properties of κ-C. Processing also affected the flow behaviour of the MP, but the effect depended on the absence or presence of cryoprotectants. EVOO would appear to provoke perceptions of creaminess/softness, whereas κ-C and XG provokes perceptions of creaminess/thickness. Very good correlations with sensory perceived consistency were found in the cases of pseudoplasticity for the FMP samples ($r^2 = 0.947$) and apparent viscosity for the F/TMP ones ($r^2 = 0.935$). These results have important implications for the production of F/TMP with improved sensory quality and freeze–thaw stability, at once that giving a functional value to the product.

Keywords: cryoprotectant, extra virgin olive oil, flow behaviour, mashed potatoes, processing, sensory analysis

Abbreviations: EVOO, extra virgin olive oil; E_w, expressible water; **κ-C**, kappa-carrageenan; **LSD**, Fisher's least significant difference; **MP**, mashed potatoes; **FMP**, fresh mashed potatoes; **F/TMP**, frozen/thawed mashed potatoes; **MPA**, mashed potatoes without added cryoprotectants; MPB, mashed potatoes with added cryoprotectants; **FMPA**, fresh mashed potatoes without added cryoprotectants; **F/TMPA**, frozen/thawed mashed potatoes without added cryoprotectants; **FMPB**, fresh mashed potatoes with added cryoprotectants; **F/TMPB**, frozen/thawed mashed potatoes with added cryoprotectants; **OA**, overall acceptability; **WHC**, water holding capacity; **XG**, xanthan gum

INTRODUCTION

Various health organizations recommend a daily intake of around 600 g of fruit and vegetables, but few people manage to consume this amount. Led by consumer demand, the food industry has shown an increased interest in the manufacture of healthier and more natural fruit and vegetable food products, such as soups, drinks and sauces (Whybrow *et al*. 2006). Mashed potatoes made from 100% fresh potato tubers are in addition a natural vegetable semi-solid food, which may also be suitable for freezing as a ready-meal component or as a product in itself such as potato gratin (Alvarez *et al*. 2009a). In addition to the advantage of extended acceptability time, frozen ready-meals also offer better manufacturing and distribution flexibility and food safety.

Among vegetable oils, extra virgin olive oil (EVOO) has nutritional and sensory characteristics that make it unique. The importance of virgin olive oil is mainly attributed both to its high content of oleic acid a balanced contribution quantity of polyunsaturated fatty acids and its richness in phenolic compounds, which act as natural antioxidants and may contribute to the prevention of several human diseases (Bendini *et al*. 2007). The polar phenolic compounds of EVOO belong to different classes: phenolic acids, phenyl ethyl alcohols, hydroxy-isochromans, flavonoids, lignans and secoiridoids. This latter family of compounds is characteristic of Oleaceae plants and secoiridoids are the main compounds of the phenolic fraction. Virgin olive oil is an integral ingredient of the Mediterranean diet and accumulating evidence suggests that it may have health benefits which include reduction of risk factors of coronary heart disease, prevention of several types of cancers, and modification of immune and inflammatory responses. EVOO can be considered as example of a functional food, with a variety of components that may contribute to its overall therapeutic characteristics (Stark and Madar 2002). Its nutritional and healthy values and pleasant flavour have contributed to an increase in consumption of virgin olive oil which has fostered cultivation of olives outside the traditional olive oil producing region of the Mediterranean basin into newer areas such as Australia, Argentina and South Africa (Bendini *et al*. 2007). The nutritional value of EVOO arises from high levels of oleic acid, and from minor components such as phytosterols, carotenoids, tocopherols and hydrophilic phenols (Pérez-Jiménez 2005).

The oil volume fraction exerts profound effects on the physicochemical and viscoelastic properties of the emulsions, such as droplet size distribution, creaming, oxidative stability, and rheology (Dickinson and Chen 1999). Fat

Received: 9 February, 2010. Accepted: 2 December, 2010.

Original Research Paper

droplets influence the overall physicochemical and sensory properties of foods in a variety of different ways (Chantrapornchai *et al*. 1999). A great deal of research has been done on the influence of fat droplets on the rheology, stability and flavour of food emulsions, but less is known about their influence on emulsion appearance. Colour is one of the major attributes affecting consumer perception of the quality of virgin olive oil (Criado *et al*. 2008), and chloroplast pigments (chlorophyll and carotenoids) are mainly responsible for the colour of virgin olive oil, ranging from yellow–green to greenish gold (Ayuso *et al*. 2004; Escolar *et al*. 2007).

Rheological techniques have increasingly been used for the characterization of food products in food and related industries in recent years. Rheological characterization is commonly based on shear stress versus shear rate ramps, which are used to characterize the shear-thinning nature of food stabilizer systems (da Silva and Rao 1992). Shear viscosity–shear stress relationships are often applied to samples to characterize them in terms of yield stress behaviour and solution viscosity in large deformation conditions (Rodd *et al*. 2000). The existence of yield stress in a material's flow indicates that there is a cross-linked or other interactive structure which must be broken down before flow can occur at an appreciable rate (Tárrega *et al*. 2006). Seven methods for determining the yield stress of concentrated suspensions were applied to natural and commercial potato purees at different temperatures, constituting a complementary set of techniques that are useful in studying the rheology of either FMP or F/TMP (Canet *et al*. 2005a).

Previous studies showed that the addition of kappa-carrageenan (*κ*-C) and xanthan gum (XG) to mashed potatoes (MP) at a low concentration (each cryoprotectant at 1.5 g kg^{-1}) is recommended on the basis of overall acceptability, especially when the product is going to be frozen (Alvarez *et al*. 2009a; Fernández *et al*. 2009). *κ*-C provides the appropriate texture, while XG imparts creaminess and mouthfeel to the product.

No research has been done on the addition of olive oil in fresh and frozen/thawed mashed potatoes, particularly with EVOO. The use of EVOO rather than commercial olive oil is preferable because of its high content of both unsaturated fatty acids and antioxidant compounds such as polyphenols and tocopherols (Severini *et al*. 2003). The purpose of the present research was to evaluate the effects of adding EVOO on the rheological, physical and sensory characteristics of fresh and frozen/thawed mashed potatoes formulated without and with added cryoprotectants.

MATERIALS AND METHODS

Test materials

The potatoes used were fresh tubers (cv. 'Kennebec') from Aguilar de Campoo (Burgos, Spain) cultivated in 2008 and having weights (g) within the confidence interval ($95.69 \leq \mu \leq 111.81$) and specific weights (g cm^{-3}) within the interval ($1.072 \leq \mu \leq 1.079$); $P \leq 0.01$. Raw material was stored in a chamber at 4 ± 1°C and 85% relative humidity throughout the experiment (Nourian *et al*. 2003). Kappa-carrageenan (*κ*-C) (GENULACTA carrageenan type LP-60) and xanthan gum (XG) (Keltrol F [E]) were donated by Premium Ingredients, S.L. (Girona, Spain). Extra virgin olive oil (EVOO) (Carbonell, Spain) was chosen to be added to the MP. Range-finding experiments were performed at the outset of these studies to ascertain the maximum acceptable amount of EVOO that could be added to the MP on the basis of texture, colour and taste. From these preliminary results, the lower and upper levels of EVOO to be used were set at 10 and 50 g kg^{-1} respectively. A sample without EVOO was also prepared for each type of MP and processing conditions.

Preparation of MP

Tubers were manually washed, peeled and diced. MP samples were prepared in ~2000-g batches by EVOO concentration, containing 607.7 g kg^{-1} of potatoes, 230.8 g kg^{-1} of semi-skimmed in-bottle sterilized milk (fat content, 15.5 g kg^{-1}), 153.8 g kg^{-1} of water, 7.7 g kg^{-1} of salt (NaCl) and the corresponding EVOO concentration (0, 10, 25, and 50 g kg^{-1}) using a Thermomix TM 31 food processor (Vorwerk España, M.S.L., S.C., Madrid, Spain). Two types of MP were prepared: without added cryoprotectants (MPA samples) and with 1.5 g kg^{-1} added *κ*-C and 1.5 g kg^{-1} added XG (MPB samples). In the latter case, *κ*-C and XG were also added to the rest of ingredients at this point in the form of a dry powder. Next, all the ingredients were heated to 90°C in the Thermomix for 5-10 min, then they were first cooked for 30 min at 90°C (blade speed: 40 rpm). During the first 5 min of this first cooking step, the ingredients were instantaneously heated to 100°C then cooled to 90°C to assure plenty enzymatic inactivation. The amount of liquid evaporated during boiling was determined by weighing the ingredients before and after cooking. The liquid was then replaced by adding milk. Next, the ingredients were cooked for an additional 5 min at 90°C. The mash was immediately triturated for 40 s (blade speed at position 4: 1200 rpm) and for 20 s (blade speed at position 5: 2600 rpm). The product was immediately homogenized through a stainless steel sieve (opening diameter: 1.5 mm). In this study, the highest EVOO concentration (50 g kg^{-1}) was added twice to the MP to evaluate the effect of order of addition and EVOO thermal treatment on MP quality. Firstly, 50 g kg^{-1} of EVOO was added along with the rest of the ingredients as indicated above, whereas in the second case the same EVOO concentration was added to the MP before final homogenization. This concentration is designated as "50b" throughout the manuscript.

Table 1 Composition and processing of the samples studied with codes used for their identification.

EVOO (g kg^{-1})	κ-C + XG (g kg^{-1})	Processing	Sample code
0	-	Fresh	FMPA0
10	-	Fresh	FMPA10
25	-	Fresh	FMPA25
50	-	Fresh	FMPA50
50b	-	Fresh	FMPA50b
0	1.5 + 1.5	Fresh	FMPB0
10	1.5 + 1.5	Fresh	FMPB10
25	1.5 + 1.5	Fresh	FMPB25
50	1.5 + 1.5	Fresh	FMPB50
50b	1.5 + 1.5	Fresh	FMPB50b
0	-	Frozen/thawed	F/TMPA0
10	-	Frozen/thawed	F/TMPA10
25	-	Frozen/thawed	F/TMPA25
50	-	Frozen/thawed	F/TMPA50
50b	-	Frozen/thawed	F/TMPA50b
0	1.5 + 1.5	Frozen/thawed	F/TMPB0
10	1.5 + 1.5	Frozen/thawed	F/TMPB10
25	1.5 + 1.5	Frozen/thawed	F/TMPB25
50	1.5 + 1.5	Frozen/thawed	F/TMPB50
50b	1.5 + 1.5	Frozen/thawed	F/TMPB50b

Two batches were continuously prepared and blended. Half of each FMP blend was analysed immediately, and the other half was frozen and thawed as reported below. Each FMP or F/TMP sample consisted of a complete batch, i.e. of ~2000 g of MP. Sample composition is shown in **Table 1**.

Freezing and thawing procedures

Following preparation, MP samples were placed on flat freezing and microwave thawing trays to minimize the differences in freezing rates between mashed potato at the surface and deep within the pack, and then frozen by forced convection with liquid nitrogen vapour in an Instron programmable chamber (model 3119-05, −70/+250°C) at −60°C until their thermal centres reached −24°C (freezing rate, 1 ± 0.10°C min^{-1}). Air and product temperatures were monitored by T-type thermocouples (NiCr/NiAl; −200 to +1000°C) using the MMS3000™ Multi Measurement System™ (Mod. T4, Commtest Instruments, Christchurch, New Zealand). After freezing, the samples were packed in 300 × 200 mm^2 rectangular polyethylene plastic bags, sealed under light

vacuum (–0.05 MPa) on a Multivac packing machine (Sepp Haggenmüller KG, Wolfertschwenden, Germany), placed in a domestic freezer for storage at −24°C and left there for at least 1 month before thawing. Packed frozen samples were thawed in a Samsung M1712N microwave oven (Samsung Electronics S.A., Madrid, Spain). Samples were always placed in the same position and heated for a total of 20 min at an output power rating of 600 W. Moisture loss by processing was determined by weighing the samples before freezing and after thawing, and the water evaporated was then remixed into the product by stirring gently with a spoon; the temperature reached at the product thermal centre was measured in all cases (+85 ± 5°C) (Fernández *et al*. 2006).

Heating of samples

All the samples were brought up to 55°C by placing them in a Hetofrig CB60VS water-bath (Heto Lab Equipment A/S, Birkerød, Denmark), where water and product temperatures were monitored by T-type thermocouples as described elsewhere (Alvarez *et al*. 2008; Fernández *et al*. 2008; Alvarez *et al*. 2009a, 2009b; Fernández *et al*. 2009). Sample testing temperature was 55°C, as previous studies have shown that this is the preferred temperature for consumption of MP (Alvarez *et al*. 2005).

Rheological measurements

A Bohlin CVR 50 controlled stress rheometer (Bohlin Instruments Ltd., Cirencester, UK) was used to conduct steady shear experiments using a plate–plate sensor system with a 2 mm gap (PP40, 40 mm) and a solvent trap to minimise moisture loss during tests. Before measurements were taken, samples remained 5 min between the plates as equilibration time. Temperature control at 55°C was achieved with a Peltier Plate system (−40 to +180°C; Bohlin Instruments).

Sample flow was measured by recording shear stress (σ) values when shearing with an increasing shear rate (γ) from 0.1 to 120 s^{-1} with a ramp of 15 min, which is the range of interest in food texture studies (Bistany and Kokini 1983). Viscosity values in the upward viscosity/shear rate curves at a shear rate of 50 s^{-1} ($\eta_{app,50}$, Pa s) were taken as the apparent viscosities of the samples. This value would represent the approximate viscosity felt in the mouth (Bourne 2002). Experimental data were fitted to the Ostwald-de Waele and Casson models using shear stress data obtained from increasing shear rate measurements (Rao 1999; Baixauli *et al*. 2004; Fernández *et al*. 2008). From the fitted models, the flow behaviour index (n) and the consistency index (K, Pa s^n), and the Casson yield stress (σ_{0C}, Pa) and the Casson plastic viscosity (η_C, Pa s) were obtained respectively. Additionally, yield stress was obtained by direct extrapolation of the straight-line portion of shear rate–shear stress data (σ_{0BM}, Pa) (Fernández *et al*. 2008).

Other quality parameters

Instrumental measurement of colour of the MP in the pots was carried out with a HunterLab model D25 (Reston, VA, USA) colour difference meter fitted with a 5 cm diameter aperture. Results were expressed in accordance with the CIELAB system with reference to illuminant D65 and a visual angle of 10°. The parameters determined were L^* ($L^* = 0$ [black] and $L^* = 100$ [white]), a^* ($-a^*$ = greenness and $+a^*$ = redness), b^* ($-b^*$ = blueness and $+b^*$ = yellowness). The total colour difference (ΔE^*) between the fresh control made without either added cryoprotectants or EVOO (FMPA0 sample, **Table 1**) and the rest of the MP samples was calculated as described elsewhere (Baixauli *et al*. 2002; Alvarez *et al*. 2008).

Expressible water (E_w) was measured by centrifugal force. Centrifuge tubes containing approximately 10 g of MP were centrifuged at 15000 × g for 30 min in a Sorvall®, RC-5B apparatus (Global Medical Instrumentation, Inc, Clearwater, Minnesota, USA). E_w was expressed as the percentage of liquid separated per total weight of sample in the centrifuge tube (Eliasson and Kim 1992). Measurements of colour and E_w were performed in quadruplicate and the results averaged.

Sensory analyses

Samples were subjected to a descriptive quantitative method adapted for MP (Adams *et al.* 1981). Sensory evaluation was conducted by a four-member panel with 8 years of specific training in potato purees (Alvarez *et al.* 2005; Canet *et al.* 2005b; Fernández *et al.* 2008). Each sample was tested twice and average scores calculated, so that each sample was tested eight times in all. The panellists were asked to evaluate samples for texture (consistency, adhesiveness, creaminess and fibrousness), appearance (authentic colour, off-colours, shine and uniformity) and taste (sweetness, authentic taste and off-taste). Scores were awarded on a scale of 1–5, in which 1 indicated total absence of the sensory attribute and 5 a very definite attribute. MP samples were also subjected to an OA test based on all sensory attributes (texture, colour, taste). In this case, sensory assessment was conducted by a fourteen-member untrained panel. The hedonic scale is used to quantify the degree of product acceptability. The hedonic nature of the test was stressed by asking the panellists to base their scores entirely on their liking of the product, and also by presenting a nine point bipolar mixed descriptive scale where each point is given a number and an explanatory description indicating the intensity of the acceptability or rejection caused by the MP. The descriptive terms for the extreme categories used were: (1 = dislike extremely, and 9 = like extremely).

Statistical analysis

As a result, two groups of 10 samples each were prepared: without and with κ-C and XG (MPA and MPB samples, respectively). Each group was divided into two subgroups, one fresh (FMP) and another one frozen/thawed (F/TMP). A sample without EVOO and samples with different concentrations (10, 25, 50 and 50b g kg^{-1}) of EVOO were prepared for each subgroup (**Table 1**). Two repetitions of each composition were made in different weeks each of them to assure the appropriate experiment randomization.

A three-way ANOVA with interactions was applied to evaluate how the three factors studied – EVOO concentration, presence or absence of hydrocolloids and performance or not of processing (freezing/thawing) – affected the steady shear measurements, colour, and the OA of the MP. E_w was always zero for all the samples containing cryoprotectants; in this case a two-way ANOVA with interactions was applied to evaluate how EVOO concentration and processing affected the WHC of the products. Minimum significant differences were calculated using Fisher's least significant difference (LSD) tests with a 99% confidence interval for the comparison of instrumental parameters, and a 95% confidence interval for comparison of OA. These analyses were performed with Statgraphics® software version 5.0 (STSC Inc., Rockville, MD, USA).

Sensory attributes from the descriptive quantitative method (discrete values) were subjected to Friedman two-factor ranked analysis of variance ($k = 10$ and $n = 8$) carried out on FMP and F/TMP samples separately, and where differences existed between samples a regular Wilcoxon signed-rank test was used to pinpoint them (O'Mahony 1986). Nonparametric tests were carried out using SPSS 14.0 software (SPSS, Inc., Chicago, IL).

RESULTS AND DISCUSSION

Characterization of flow curves of MP

Flow curves of both FMPB and F/TMPB samples at different EVOO concentrations (0, 50 and 50b g kg^{-1}) are shown in **Fig. 1**. The variation of the shear stress values with the shear rate indicated a non-Newtonian shear-thinning flow ($n < 1$) and yield stress with all the added combinations. Curves were similar at other EVOO concentrations. Earlier studies have also shown that MP samples are non-Newtonian at most temperatures (Canet *et al*. 2005b). The rheology of gums and stabilizers is generally non-Newtonian and they impart a non-Newtonian character to dressings and sauces even when the amount of the dispersed phase is small (Ford *et al*. 1997). The pseudoplastic behaviour of MP was due to the flow behaviour of potato starch

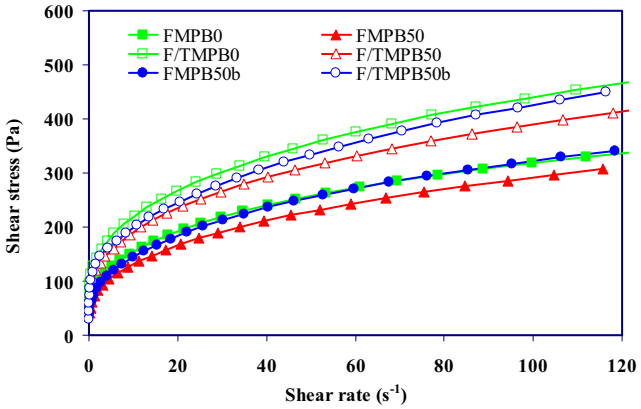

Fig. 1 Typical flow curves showing the changes in shear stress for both FMPB and F/TMPB samples without added EVOO and with 50 and 50b g kg^{-1} added EVOO.

and biopolymers. Starch blends can be pseudoplastic (BeMiller and Whistler 1996), especially when granules are significantly swollen, so that they become deformed when subjected to shear force (Bagley and Christianson 1982). F/TMPB samples presented higher resistance to flow than their FMPB counterparts (**Fig. 1**). F/TMPB0 sample, followed by F/TMPB50b and F/TMPB50 samples exhibited a higher shear stress compared to their FMPB counterparts, indicating that F/TMPB products were more structured. This behaviour can be explained taking account that much stronger and more cohesive networks are formed when solutions of XG are frozen and thawed (Giannouli and Morris 2003). Accordingly to these authors, during freezing, XG chains are forced to align and associate by conversion of water to ice crystals. The forced associations survive on thawing to give a cryogel network. Nevertheless, XG avoid amylose retrogradation, but it does not prevent ice recrystallization nor amylopectin retrogradation (Ferrero *et al*. 1994); therefore, mainly amylopectin retrogradation could also be responsible of the overall structure reinforcement observed in the processed samples.

On visually comparing flow curves of FMPB and F/TMPB samples made without and with 50 g kg^{-1} added EVOO, one can observe that the shear stress was greater in the samples without added EVOO. This seems to indicate that the flow behaviour of the systems is not only influenced by the presence of starch, cryoprotectants and processing, but also by the presence of fat that can affect their structure (Tárrega and Costell 2006). Note as in both F/TMPB and FMPB samples, the flow curve were greater when the EVOO was added after cooking (50b g kg^{-1}). This difference could be related to the droplet size in the systems. In this study oil droplet diameters were not measured, but it is very probably that MP with added EVOO before final homogenization had larger droplets sizes because they were not drastically triturated. Lower differences in the flow curves of the FMPB samples could be associated with greater orientation of macromolecules and structural disruption (Windhab 1995).

Effect of EVOO concentration, cryoprotectant addition and freezing and thawing processes on steady shear measurements of MP

Table 2 shows the effects of EVOO concentration, cryoprotectant addition and processing on the values of the rheological properties derived from the flow curves. *F** ratios are not shown, but generally speaking the addition of cryoprotectants was the factor that set the main differences among the steady measurements of the samples, followed by processing and the EVOO concentration (in that order). However, in the case of the consistency index (*K*), processing was the factor that set the main differences, followed by the EVOO concentration and the addition of cryoprotectants (in that order). MPB samples presented significantly higher rheological properties than their MPA counterparts. As mentioned earlier, previous studies shown that when κ-C/XG blends were added to FMP and F/TMP samples, κ-C provided the appropriate consistency whereas XG imparted creaminess to the product (Alvarez *et al*. 2009a; Fernández *et al*. 2009). Analogously, in starch/XG blends, it was observed that XG does not interfere in potato starch network building (Mandala and Palogou 2003; Mandala *et al*. 2004). Therefore, addition of both hydrocolloids to MP produces to a more structured system which is associated with the gelling properties of κ-C. The effect of XG on creaminess would be explained by either amylose/XG interactions preventing retrogradation or XG-water interactions as commented below. Note as the flow behaviour index (*n*), which indicates the extent of shear-thinning behaviour as it deviates from 1, was also higher in the MPB samples than in the MPA ones. The more intense shear-thinning behaviour observed in MPA samples could be due to high concentration of a high molecular weight substance (potato starch) in the liquid phase not competing with other biopolymers, as reported by Holdsworth (1971).

In turn, F/TMP samples presented significantly higher $\eta_{app,50}$, *n* and $\eta_{C,}$ but lower *K*, σ_{0C} and σ_{0BM} values than their FMP counterparts. In natural MP without added cryoprotectants, the product was softer than the fresh control after freezing and thawing (Alvarez *et al*. 2005). Also, processing weakened the structure of natural MP without added cryoprotectants at different experimental temperatures, producing a far more diluted dispersion (Alvarez *et al*. 2004). MP may be considered starchy foods, and as such may present quality problems such as syneresis and organoleptic and textural changes, especially if they are subjected to freeze-thaw cycles. These problems were ascribed to phase separation caused by retrogradation of the starch (Eliasson and Kim 1992; Kim and Eliasson 1993; Kim *et al*. 1993). One strategy to minimise damage from freezing is to incorporate compounds that interact with water and offer protection against the deleterious effects of thawing in particular, i.e. cryoprotectants (Sych *et al*. 1990), which have been reported to slow down the rate of ice crystal growth and alter crystal shapes (Bolliger *et al*. 2000).

With respect to the effect of the EVOO addition, the maximum $\eta_{app,50}$, *K*, σ_{0C} and σ_{0BM} values were registered in the samples without EVOO, although the differences between σ_{0C} values of the samples with 10 g kg^{-1} added EVOO and those without EVOO were non-significant (**Table 2**). Adding 25 and 50 g kg^{-1} of EVOO (either before or after cooking) significantly reduced consistency (*K*) and both yield stresses (σ_{0C} and σ_{0BM}). By contrary, an increase in EVOO concentration produced an increase in the flow index value (*n*). Generally speaking, increasing EVOO concentration produced softer, liquid-like systems. Increasing oil content in mayonnaise reduced the elasticity more than the viscosity but also reduced the yield value (Štern *et al*. 2007). This softening associated with increased EVOO content is to be expected as liquid oil in rising concentration is added to the product, increasing the oil-phase volume fraction. In oil-in-water emulsions, the extent of the linear region decreased with increasing oil-phase volume fraction from 20% to 40% v/v (Sun and Gunasekaran 2009). In turn, Dickinson and Chen (1999) suggested that oil/water emulsions may undergo a behaviour transition from predominantly entropic behaviour to predominantly enthalpic behaviour with increasing oil-phase volume fraction. So the 20% (v/v) oil/water emulsions behaved as polymer gels (strain hardening, long linear region, and large rupture strain), while the 40% (v/v) oil/water emulsions behaved as particle gels (strain weakening, short linear region, small rupture strain). However, note that Casson plastic viscosity (η_C) significantly increased with both 50 and 50b g kg^{-1}. A possible mechanism by which oil increases η_C includes lubrication (de Wijk *et al*. 2003).

The analysis of variance also showed that the three binary interactions among the factors under consideration

Table 2 Effects of EVOO concentration, cryoprotectant addition and freezing/thawing (processing) on rheological properties of MP.

Source	Apparent viscosity at 50 s^{-1}, $\eta_{app,\,50}$ (Pa s)	Flow behaviour index, n (-)	Consistency index, K (Pa s^n)	Casson yield stress, σ_{0C} (Pa)	Casson plastic viscosity, η_C (Pa s)	Yield stress from Bingham method, σ_{0BM} (Pa)
Main effects:						
A:EVOO concentration (g kg^{-1})						
0	4.940 a	0.208 b	113.542 a	83.290 a	0.798 b, c	181.875 a
10	4.074 b	0.182 a	102.642 b	79.324 a	0.629 a	159.375 b
25	4.255 b	0.223 b	89.180 c	70.600 b	0.728 a, b	155.000 b
50	4.112 b	0.284 c	66.701 d	52.435 d	0.884 c, d	143.125 c
50b	4.308 b	0.265 c	73.455 d	59.899 c	0.908 d	153.750 b
P values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (99%)	0.266	0.024	9.051	5.276	0.109	8.034
B:Cryoprotectant addition						
Without κ-C and XG	3.064 a	0.183 a	85.714 a	60.918 a	0.458 a	116.500 a
With κ-C and XG	5.611 b	0.282 b	92.494 b	77.301 b	1.121 b	200.750 b
P values	<0.001	<0.001	0.0030	<0.001	<0.001	<0.001
LSD (99%)	0.168	0.015	5.724	3.337	0.069	5.081
C:Processing						
Fresh	4.148 a	0.202 a	98.992 a	78.333 a	0.623 a	168.750 a
Frozen/thawed	4.527 b	0.263 b	79.216 b	59.886 b	0.956 b	148.500 b
P values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (99%)	0.168	0.015	5.724	3.337	0.069	5.081
Interactions						
AB	<0.001	<0.001	<0.001	<0.001	0.0017	<0.001
AC	<0.001	0.1919	<0.001	<0.001	<0.001	<0.001
BC	<0.001	<0.001	<0.001	<0.001	0.1262	<0.001
ABC	<0.001	0.0154	<0.001	<0.001	<0.001	<0.001

had a significant effect on the $\eta_{app,50}$, K, σ_{0C} and σ_{0BM} values (**Table 2**). This means that the effect of EVOO concentration on the rheological properties of the samples depended on the presence of κ-C and XG and on the freezing/thawing of the systems. Besides, the interactions between EVOO concentration and cryoprotectant addition and between this and processing significantly affected the value of n, whereas binary interactions AB and AC were also found to have a significant effect on the value of η_C.

From the variation in the $\eta_{app,50}$ value based on EVOO concentration for both MPA and MPB samples shown in **Fig. 2A**, one can observe that in all cases $\eta_{app,50}$ was lower in the MPA than in the MPB samples containing cryoprotectants. Therefore, MPB samples were thicker which is attributed to the presence of κ-C in the systems as shown previously (Alvarez *et al*. 2009a; Fernández *et al*. 2009). In both MPA and MPB samples, the changes in the values of $\eta_{app,50}$ were similar when EVOO concentration increased from 10 to 50 g kg^{-1}. However, with 50b g kg^{-1} EVOO concentration the $\eta_{app,50}$ value developed differently for each type of sample. In the MPB samples, adding 50b g kg^{-1} of EVOO increased the value of $\eta_{app,50}$, indicating a recovering of the original structure of the system, whereas the addition of oil at this same concentration produced a significant weakening of the original structure in the case of the MPA samples. Addition of XG to pourable salad dressings induces depletion flocculation of the droplets and formation of a three-dimensional weak gel network structure that retards the process of droplet creaming (Parker *et al*. 1995). However, in the MPB samples when EVOO was added after cooking, it was not totally entrapped in the MP matrix, and larger oil droplets probably formed by aggregation through steric and/or electrostatic forces (Paraskevopoulou *et al*. 2005). Also, when the concentration of added EVOO was increased, the $\eta_{app,50}$ value developed differently in the FMP and F/TMP samples (**Fig. 2B**); in FMP samples, the increase in EVOO content led to reduced apparent viscosity. As the droplet concentration increased, the droplets are polydisperse and the samples present a less close packing structure. In mayonnaise, increasing walnut oil content increases the diameter of oil droplets and consequently reduces viscoelastic properties (Cavella *et al*. 2009). However, in the F/TMP samples, adding 50b g kg^{-1} EVOO increased sample viscosity up to a value almost similar to that observed in the control. Freezing and thawing significantly increased sample viscosity in the systems with 50 and 50b g kg^{-1} EVOO, although in the lowest EVOO concentrations the viscosity of the FMP and F/TMP samples was similar. The processing-dependent variation in $\eta_{app,50}$ value based differed in the MPA and MPB samples (**Fig. 2C**). Processing significantly decreased sample viscosity in the MPA samples but significantly increased it in MPB samples. This behaviour can be explained taking account that much stronger and more cohesive networks are formed when solutions of XG are frozen and thawed (Giannouli and Morris 2003). The effect of XG may be explained by amylose/XG interactions, which compete against amylose/amylose interactions, retarding or even avoiding retrogradation and softening. Recently, it has also been shown that the addition of small amounts of XG to white sauces made with starches from different sources significantly improve freeze/thaw stability (Aroca *et al*. 2009).

The variation in n value with EVOO concentration for both MPA and MPB samples is shown in the **Fig. 2D**. In the MPB systems, when the EVOO concentration was increased the value of n slightly increased, indicating that the addition of this ingredient produced a slight decrease of pseudoplasticity. In the MPA samples, adding 10 g kg^{-1} EVOO significantly increased pseudoplasticity as compared with the control without EVOO, but clearly decreased when EVOO was added at the highest concentration. Note that the n value was lower when the EVOO was added after cooking (50b g kg^{-1}) in the MPA samples but not in the MPB samples. When the processing-dependent variation in n value was plotted (**Fig. 2E**), the changes in the parameter value were similar to those observed for the $\eta_{app,50}$ (**Fig. 2C**), although the effect of processing on the flow index value was more pronounced, particularly in the MPA samples. Anyway, either the percentage of added EVOO or processing had a much less important effect on the pseudoplasticity in the systems containing κ-C and XG, evidencing the ability of this blend of cryoprotectants to improve freeze/thaw stability of MP (Alvarez *et al*. 2009a; Fernández *et al*. 2009), as well as to mitigate the effect of the addition of other ingredients, such as EVOO.

The changes in the values of K on increasing EVOO concentration in both MPA and MPB samples (**Fig. 2F**) were quite similar to those observed in the $\eta_{app,50}$ values

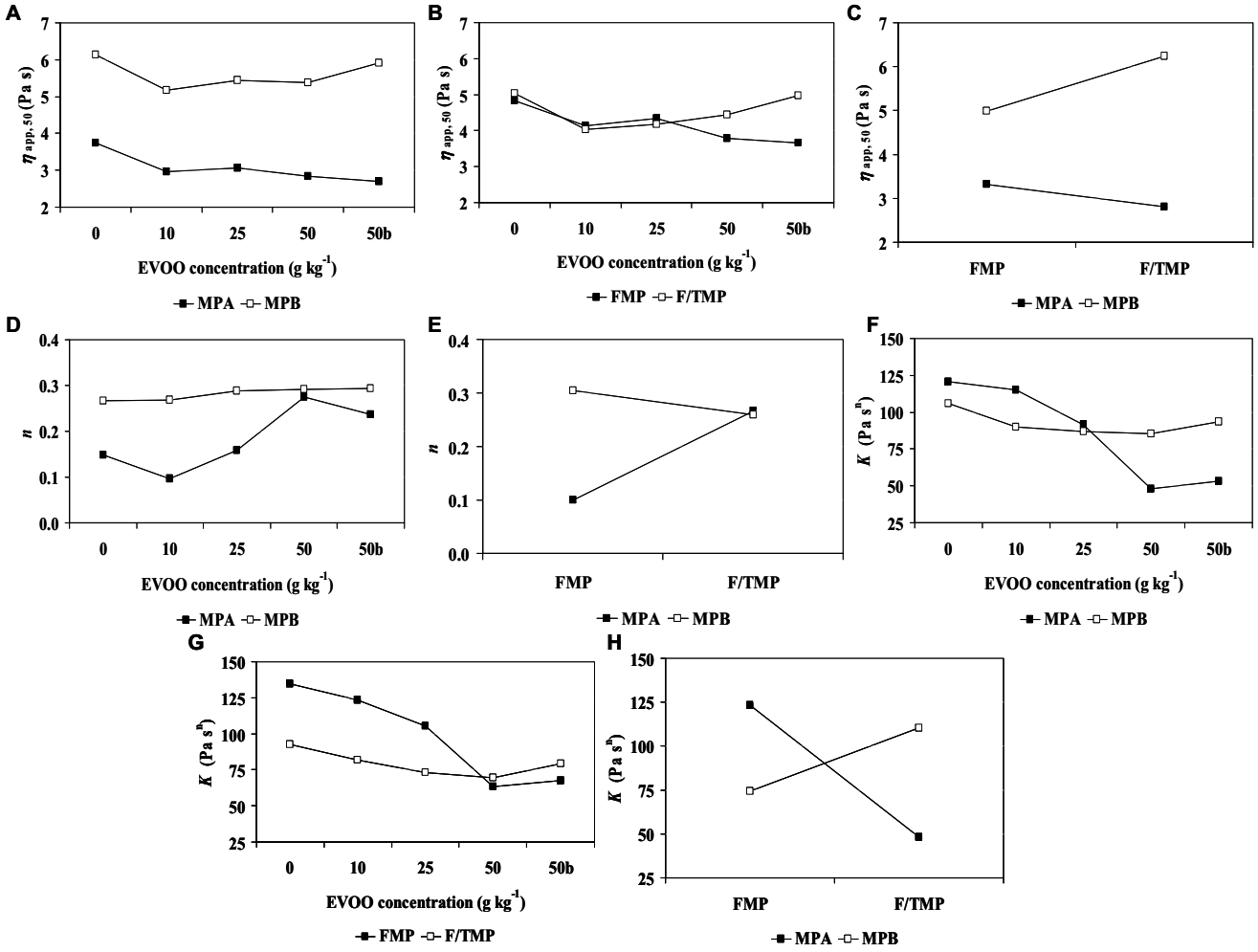

Fig. 2 Apparent viscosity value at 50 s^{-1} of: (**A**) MPA and MPB samples at different EVOO concentrations; (**B**) FMP and F/TMP samples at different EVOO concentrations; (**C**) MPA and MPB samples for both processing conditions. Flow behaviour index value of: (**D**) MPA and MPB samples at different EVOO concentrations; (**E**) MPA and MPB samples for both processing conditions. Consistency index value of: (**F**) MPA and MPB samples at different EVOO concentrations; (**G**) FMP and F/TMP samples at different EVOO concentrations; (**H**) MPA and MPB samples for both processing conditions.

(**Fig. 2A**). In addition, the decrease in MPA sample consistency was greater when EVOO concentration increased from 10 to 50 g kg^{-1}; moreover, the *K* value was higher for the MPA samples when the EVOO concentration was lower (0 to 25 g kg^{-1}). When the EVOO concentration was increased, the *K* value evolved similarly for each of the FMP and F/TMP products (**Fig. 2G**). At 0, 10 and 25 g kg^{-1} EVOO concentration, FMP samples showed significantly higher consistency values than F/TMP samples, whereas in the systems with 50 g kg^{-1}, this was the case for the F/TMP samples. Besides, for the MPB samples, processing significantly increased sample consistency; whereas, for the MPA samples, it decreased remarkably (**Fig. 2H**).

Nevertheless, on representing the variation in the Casson yield stress (σ_{0C}) value based on EVOO concentration for both MPA and MPB samples (**Fig. 3A**), it can be observed that in the MPA samples the addition of 25, 50 or 50b g kg^{-1} EVOO significantly decreased σ_{0C} while the addition of EVOO at concentrations of 10 g kg^{-1} slightly increased σ_{0C} values. In the MPB samples, addition of 10-50 g kg^{-1} EVOO significantly decreased Casson yield stress; moreover, the variation in σ_{0C} was lower in presence of κ-C and XG. In both FMP and F/TMP products the variation in σ_{0C} with EVOO concentration was quite similar to that observed in the values of *K* (**Fig. 2G**) (data are not shown). In addition, processing significantly decreased Casson yield stress value in the MPA samples but significantly increased it in MPB samples (**Fig. 3B**). Curiously, when the percentage of added EVOO was increased, the η_C value behaved similarly for both MPA and MPB samples (**Fig. 3C**) and for both FMP and F/TMP ones (**Fig. 3D**). In all cases, η_C values were greater in the samples with added cryoprotectants and likewise in the processed products. In both MPA and FMP products, samples with 50 g kg^{-1} added EVOO had the highest η_C values, while samples with 10 g kg^{-1} added EVOO had lower η_C values than the EVOO-free control. In turn, in both MPB and F/MP products when the amount of added EVOO was increased, only the samples with 50b g kg^{-1} added EVOO had significantly higher η_C values than the EVOO-free control.

Finally, the variation in the σ_{0BM} value based on EVOO concentration for both MPA and MPB samples is shown in the **Fig. 2E**. In the MPA samples, on increasing the percentage of added EVOO the value of σ_{0BM} significantly decreased, without significant differences between the parameter values for the samples with 50 and 50b g kg^{-1} added EVOO. This result evidences that in MPA samples, the structure responsible for the yield stress is weakened by adding this ingredient. In the MPB samples, EVOO concentration had a less remarkable effect. The σ_{0BM} values were lowest in the samples with added EVOO, although the differences between samples with 10, 25 and 50 g kg^{-1} added EVOO were not significant. On the other hand, adding 50b g kg^{-1} EVOO did not significantly decreased the σ_{0BM} value as compared to the value obtained in the control without added EVOO. In both FMP and F/TMP products the variation in yield stress with EVOO concentration was quite similar to that observed in the sample consistency (**Fig. 2F**) (data are not shown). On representing the variation in the yield stress from Bingham method based on processing (**Fig.**

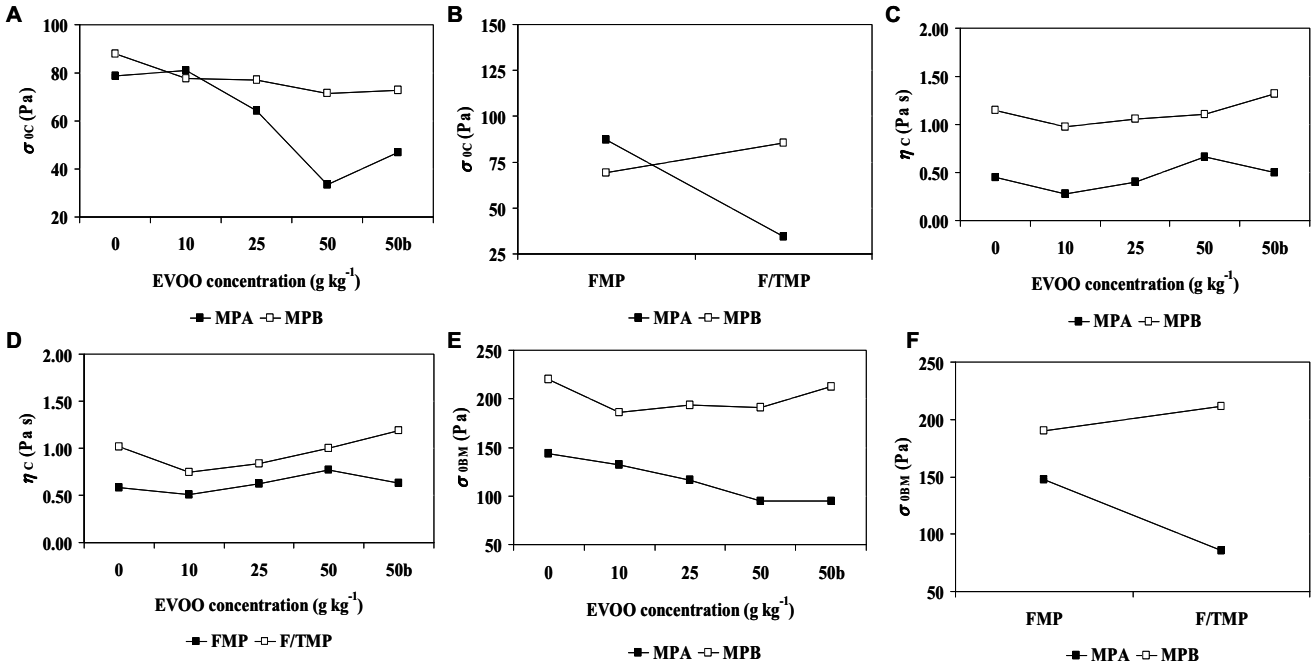

Fig. 3 Casson yield stress value of: (**A**) MPA and MPB samples at different EVOO concentrations; (**B**) MPA and MPB samples for both processing conditions. Casson plastic viscosity value of: (**C**) MPA and MPB samples at different EVOO concentrations; (**D**) FMP and F/TMP samples at different EVOO concentrations; Bingham yield stress value of: (**E**) MPA and MPB samples at different EVOO concentrations; (**F**) MPA and MPB samples for both processing conditions.

2F), the changes in parameter value were similar to those observed for the $\eta_{app,50}$ (**Fig. 2C**), although in the yield stress parameter, processing had a less remarkable effect in the MPB samples. These results would appear to indicate a positive effect whereby freeze-thawing resistance and stability were imparted to MP when XG was added, combined with κ-C.

Effect of EVOO concentration, cryoprotectant addition and freezing and thawing processes on other quality parameters of MP

Instrumental colour was found to significantly change with EVOO concentration, cryoprotectant addition and processing (**Table 3**). All the three main factors studied and their interactions were found to have a significant effect on the colour differences with respect to the fresh control without added ingredients (FMPA0 sample, **Table 1**). As the EVOO concentration increased there was an increase in the ΔE* value. An increase in EVOO level favours higher *L** value (lightness) due to an increase in the overall light scattering associated with the scattering properties of fat (Chantrapornchai *et al*. 1999). The maximum ΔE* value corresponded to the samples with 50 g kg^{-1} added EVOO, and the value of the parameter for the samples with 50b g kg^{-1} added EVOO was significantly lower. MPB and F/TMP samples presented significantly higher ΔE* values than their respective MPA and FMP counterparts. Increased colour differences in the F/TMP samples as compared to the ΔE* values in their FTM counterparts may have been partly due to the formation of fissures produced by the growth of ice crystals during freezing, which favours the release of water; this would transmit the light more rather than capturing it.

On representing the ΔE* values on EVOO concentration for both FMA and FMB samples (**Fig. 4A**), one can observe that the colour differences with respect to the fresh control without added ingredients were higher in the MPB samples than in their MPA counterparts, which could be partially due to the absolute water holding capacity (WHC) of the MPB samples as discussed below, as well as to a loss of greenness related to the presence of XG in the system as found previously (Fernández *et al*. 2008). Also, as the EVOO concentration increased there was in increase in ΔE* in both MPA and MPB samples. The influence of droplet characteristics on the optical properties of coloured oil-in-water emulsions was examined (Chantrapornchai *et al*. 1999). The lightness (*L**) of the emulsions increased with increasing droplet concentration and decreasing droplet size. As the droplet concentration increases so does the reflectance because the droplets scatter light more effectively and hence the light beam is unable to penetrate further into the product and be absorbed. Consequently, ΔE* values increased as EVOO concentration increased because the

Table 3 Effects of EVOO concentration, cryoprotectant addition and freezing/thawing (processing) on colour, expressible water and OA of MP.

Source	ΔE*	Ew (%)	OA
Main effects:			
A: EVOO concentration (g kg^{-1})			
0	1.386 a	22.421 b	5.025 a
10	3.537 b	25.733 a	7.266 b
25	4.813 c	20.716 d	7.744 c
50	7.898 d	21.523 c	8.169 d
50b	7.538 e	21.854 b, c	8.006 d
P values	<0.001	<0.001	<0.001
LSD (99%)	0.069	0.710	0.246
B: Cryoprotectant addition			
Without κ-C and XG	3.921 a	-	7.089 a
With κ-C and XG	6.147 b	-	7.395 b
P values	<0.001	-	<0.001
LSD (99%)	0.043	-	0.156
C: Processing			
Fresh	4.621 a	21.010 a	7.022 a
Frozen/thawed	5.448 b	23.888 b	7.461 b
P values	<0.001	<0.001	<0.001
LSD (99%)	0.043	0.449	0.156
Interactions			
AB	<0.001	-	<0.001
AC	<0.001	<0.001	0.0775
BC	<0.001	-	0.5200
ABC	<0.001	-	<0.001

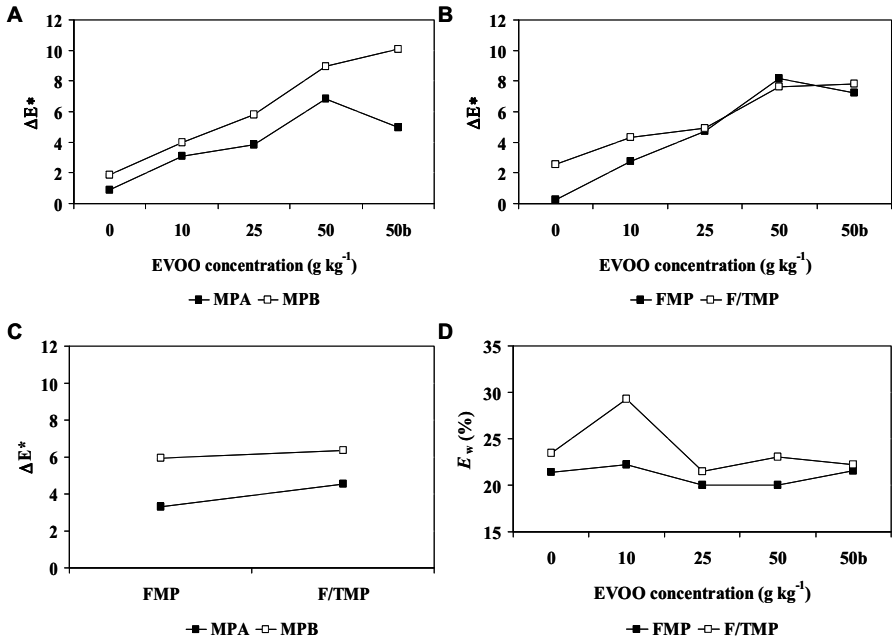

Fig. 4 Colour difference value of: (**A**) MPA and MPB samples at different EVOO concentrations; (**B**) FMP and F/TMP samples at different EVOO concentrations; (**C**) MPA and MPB samples for both processing conditions. Expressible water value of: (**D**) FMP and F/TMP samples at different EVOO concentrations.

amount of light reflected from them increased relatively uniformly across the whole wavelength range. However, probably, this increase is also associated with the augmented pigment content of the MP. The pigment profile of the virgin olive oil comprises chlorophyll *a*, chlorophyll *b*, and derivative pigments associated with the acidic medium of the oil extraction process: pheophytin *a*, pheophytin *b*; and the carotenoids: lutein, β-carotene and the epoxide xanthophylls, neoxanthin, violaxanthin and antheraxanthin (Criado *et al*. 2008).

Note that in the MPB samples the ΔE* value was greater when the EVOO was added after cooking (50b g kg^{-1}), whereas in the MPA systems it was greater in the samples with 50 g kg^{-1} EVOO added before cooking (**Fig. 4A**). This discrepancy could be also related to either the droplet size or the presence of cryoprotectants in the systems. MP with added EVOO before final homogenization would be expected to have larger droplets because the sample was not thoroughly triturated. In the presence of XG, there is an increase in the reflectance in the MP with added EVOO before final homogenization; this is because in absence of creaming and coalescence, the droplets scatter light more effectively when the oil is not so strongly entrapped in the matrix. In the MPA samples on the other hand, reflectance probably decreased because the scattering efficiency of the droplets decreases above a certain droplet size.

Analogously, on increasing the percentage of added EVOO, the ΔE* values developed similarly for each of the two FMP and F/TMP samples (**Fig. 4B**). In fact, the ΔE* values were higher in processed than in fresh samples only when smaller EVOO concentrations (0 and 10 g kg^{-1}) were added. Processing significantly increased sample colour difference in both MPA and MPB samples, although the effect of processing on the ΔE* value was less pronounced in the case of the MPB samples (**Fig. 4C**).

In turn, E_w was found to significantly change with EVOO concentration and processing (**Table 3**). In addition, the binary interaction among the two factors had a significant effect on the WHC of the samples (**Fig. 4D**). In this study, addition of κ-C and XG reduced the E_w of both FMP and F/TMP samples to 0.00%, corroborating the well-established ability of XG to immobilize water as found previously (Lee *et al*. 2002; Alvarez *et al*. 2008, 2009a), and evidencing the existence of XG-water or XG-water-XG interactions in the systems. Also, according to Baranowska *et al.* (2008), the amount and mobility of free water is limited in the presence of XG. Addition of κ-C alone significantly reduces the water loss in F/TMP samples (Alvarez *et al*. 2009), but in the presence of either κ-C and XG blends at different concentrations or of XG alone, the release of liquid completely disappeared as also found in this study. Analogously, adding XG (0.3% w/w) to corn starch pastes (10% w/w) minimized syneresis after freezing (Ferrero *et al.* 1993, 1994; Ferrero and Zaritzky 2000). In turn, Lee *et al*. (2002) found the effect of XG to be dependent on concentration; at a concentration of 0.3% the XG was more effective than guar gum in reducing syneresis in a freeze/thawed potato starch gel; however, at 0.6% the guar gum was more effective. The authors hypothesized that starch/XG interaction was excessive at 0.6%, resulting in a negative effect on syneresis by allowing more water to transform to bulk phase ice. The addition of XG also significantly reduced the appearance of syneresis in white sauces made with potato starches (Aroca *et al*. 2009). In any case the E_w values recorded in the present case confirm that XG effectively stabilizes MP against syneresis when no more than 1.5 g kg^{-1} is added.

As regards EVOO concentration and processing effects and the binary interaction between the two factors (**Fig. 4D**), WHC was greater in the FMP samples than in their F/TMP counterparts at all EVOO concentrations. This result is likely related to structural damage caused by freezing. The fissures formed by the growth of ice crystals during freezing, favour the release of water as indicated above. The addition of EVOO at low concentrations significantly increased E_w, mainly in the processed samples. The reason for the greater water loss resulting from the addition of EVOO at 10 g kg^{-1} may have been that the interchain spaces were occupied by oil, displacing the water (Liehr and Kuliche 1996). However, the addition of EVOO at higher concentrations again significantly reduced water loss, probably because excess oil hindered the release of water from the starch matrix. EVOO by itself was not effective in enhancing the WHC of MP. In any case E_w percentages were also quite high (> 20) in both FMP and F/TMP samples without added EVOO, evidencing the presence of weak starch-water or starch-water-starch interactions in all the systems. Water separation in the MP without added cryoprotectants is due to starch retrogradation and a consequent reduction of water holding ability (BeMiller and Whistler 1996).

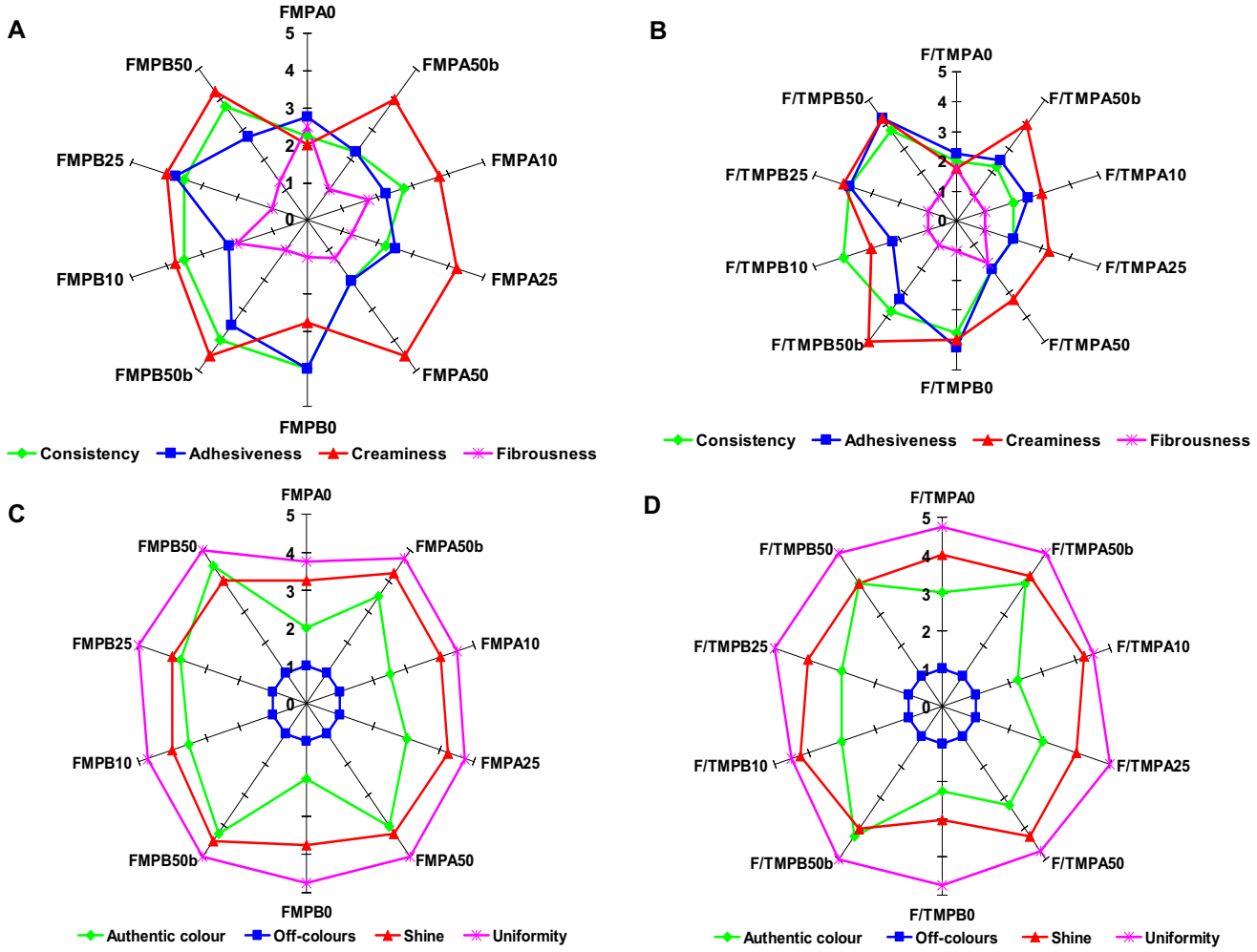

Fig. 5 (**A**) Sensory texture attributes of FMP. (**B**) Sensory texture attributes of F/TMP. (**C**) Sensory appearance attributes of FMP. (**D**) Sensory appearance attributes of F/TMP. Identification of system notation in **Table 1**.

Effect of EVOO concentration, cryoprotectant addition and freezing and thawing processes on sensory attributes and OA of MP

The Friedman test showed that there were significant differences between FMP samples due to EVOO concentration and cryoprotectant addition as regards to consistency, adhesiveness, creaminess and fibrousness (χ^2 = 60.43, χ^2 = 54.85, χ^2 = 58.46 and χ^2 = 40.74, respectively; p = 0.000), authentic colour, shine and uniformity (χ^2 = 61.43, χ^2 = 33.96 and χ^2 = 39.26, respectively; p = 0.000) and authentic taste (χ^2 = 25.25; p = 0.003). The panellists detected no effect of EVOO concentration and cryoprotectant addition on off-colours, sweetness or off-taste in the FMP products. On the other hand there were significant differences between F/TMP samples as regards to consistency, adhesiveness, creaminess and fibrousness (χ^2 = 65.71, χ^2 = 52.88, χ^2 = 58.44 and χ^2 = 54.00, respectively; p = 0.000), authentic colour, shine and uniformity (χ^2 = 60.86, χ^2 = 45.05 and χ^2 = 21.89, respectively; p = 0.000) and sweetness (χ^2 = 25.65; p = 0.002). The panellists detected no effect of EVOO concentration and cryoprotectant addition on off-colours, authentic taste or off-taste in the F/TMP products. In addition, all the three main factors significantly affected the OA of the products (P < 0.05) (**Table 3**). Moreover, the interaction between EVOO concentration and cryoprotectant addition significantly affected the value of the OA of the samples.

Figs. 5 and **6** show radar plots constructed to represent perceived sensory attributes and the OA. As regards to the sensory attributes of texture in FMP samples (**Fig. 5A**), in the case of consistency the panellists distinguished significantly between FMPA50 sample, which scored lowest, and all the other samples (except for FMPA0, FMPA25 and FMPA50b samples). In the case of adhesiveness, the panellists distinguished significantly between FMPB0 sample and all the other samples (except for FMPB25). Therefore, sensory analysis indicated that 50 g kg^{-1} EVOO provided superior softening in the MPA samples, whereas addition of cryoprotectants provided better thickening. In the case of creaminess, the panellists distinguished significantly between FMPB50b and all the other samples (although differences between FMPB50b, FMPB50, FMPA50 and FMPA25 samples were non-significant), which scored highest for creaminess and presented a softer mouthfeel. Therefore, addition of EVOO at the highest concentration used, either in presence or in absence of cryoprotectants, increased the creaminess of the samples. In this study, the panellists also scored the FMPA0 control higher for fibrousness than any of the other samples.

In the F/TMP products (**Fig. 5B**), the panellists scored F/TMB10 sample higher for consistency, although differences with F/TMB0, F/TMPB25, F/TMPB50 and F/TMPB50b were non-significant. This result again points out the freeze-thaw stability conferred by the κ-C/XG blend. In the case of adhesiveness, the panellists distinguished significantly between F/TMPB0 and all the other samples (except for F/TMPB50), which scored higher. Conversely, F/TMPA products without added cryoprotectants scored lower for the adhesiveness. In the case of creaminess, the panellists distinguished significantly between F/TMPB50b and all the other samples, which scored higher. The panellists perceived more fibrousness in the F/TMPA0 and F/TMPA50 samples, in both of which there was no cryoprotectants. This could be ascribed to the lack of hydro-

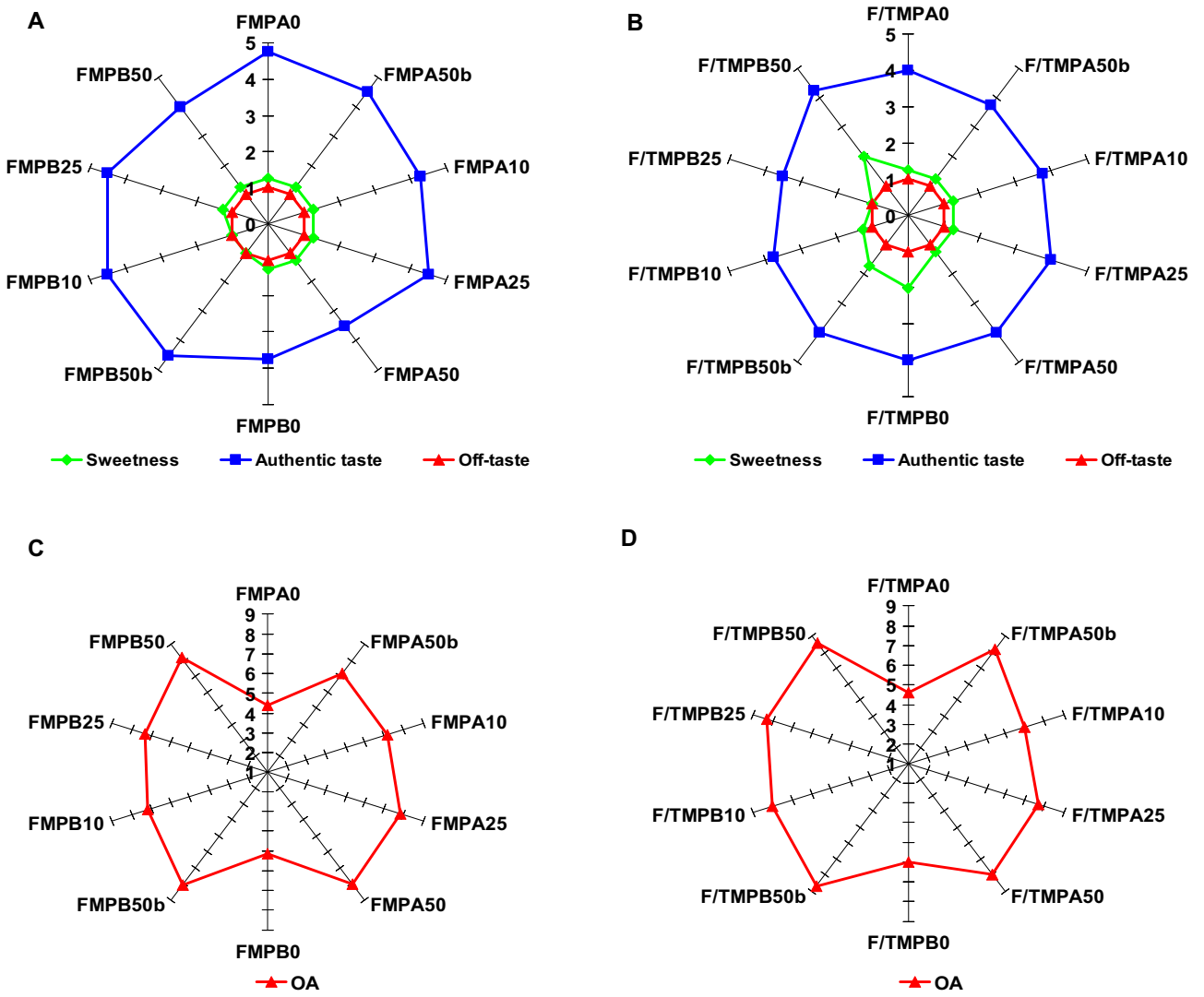

Fig. 6 (**A**) Sensory taste attributes of FMP. (**B**) Sensory taste attributes of F/TMP. (**C**) Overall acceptability (OA) of FMP. (**D**) Overall acceptability (OA) of F/TMP. Identification of system notation in **Table 1**.

colloid–water interactions in the absence of XG, as well as to the presence of larger aggregates of retrograded starch, which were detected by the panellists.

As regards to sensory appearance attributes (**Fig. 5C**), of the FMP samples, FMPB50 scored highest for authentic colour, although the differences between the score for this sample, and that for F/TMPB50b were non-significant. Therefore, addition of either cryoprotectants or of EVOO at a high enough concentration improved the colour of FMP products. The panellists may have found that increasing yellowness improved the colour of the product, since the flesh of Kennebec potatoes is white and MP without added other ingredients look rather pale. In fact, the panellists also distinguished significantly between FMPA0 control and the rest of the FMP samples, which scored lower for uniformity and shine. Of the F/TMP products (**Fig. 5D**), F/TMPA10 scored lowest for authentic colour, although the differences between the score for this sample, and that for F/TMPB0 were non-significant. The panellists scored F/TMB50b sample higher for authentic colour, although differences with F/TMPB50 sample were non-significant. F/TMPB0 control with added biopolymers scored lower for shine than the rest of the samples, which is likely related to the lack of EVOO in the controls. The panellists distinguished significantly between F/TMPA10, which scored lowest for uniformity, and all the other samples (except for F/TMA0, F/TMPA50 and F/TMPB0).

As regards to sensory taste attributes, of the FMP samples, in the case of authentic taste, the panellists distinguished significantly between the FMPA0 control, which scored highest, and FMPB0 and FMPA50 samples, which scored lowest (**Fig. 6A**).The former is related to the potato taste detected by the panellists in the samples without other added ingredients. However, the addition of EVOO clearly improved the taste of FMP, as evidenced by the highest OA score received by all the samples containing EVOO as shown below. Of the F/TMP products (**Fig. 6B**), the panellists distinguished significantly between F/TMPA0, which scored lowest for sweetness, and F/TMPB0 and F/TMPB50 samples, which scored highest. This indicates that addition of cryoprotectants increased the sugariness of the F/TMP samples.

Finally, note as scores for OA increased significantly with increasing EVOO content in both fresh and processed MPA and MPB samples (**Figs. 6C, 6D**). Similarly, a positive relationship between oil content and sensory acceptability has been observed in a set of Polish commercial mayonnaises (Juszack *et al.* 2003) and in salami (Severini *et al*. 2003). Also, sensory acceptability has been found to increase with increasing oil content in mayonnaise (Štern *et al*. 2007). The creamy mouthfeel, and smooth and thick texture contribute substantially to the sensory acceptability of mayonnaise. Anyway, the effect of EVOO content on both rheological and sensory characteristics of MP is rather complicated in the presence of cryoprotectants, since both the hydrocolloids and the oil content have pronounced effects on these properties. The main differences between samples without and with added EVOO were ascribed to

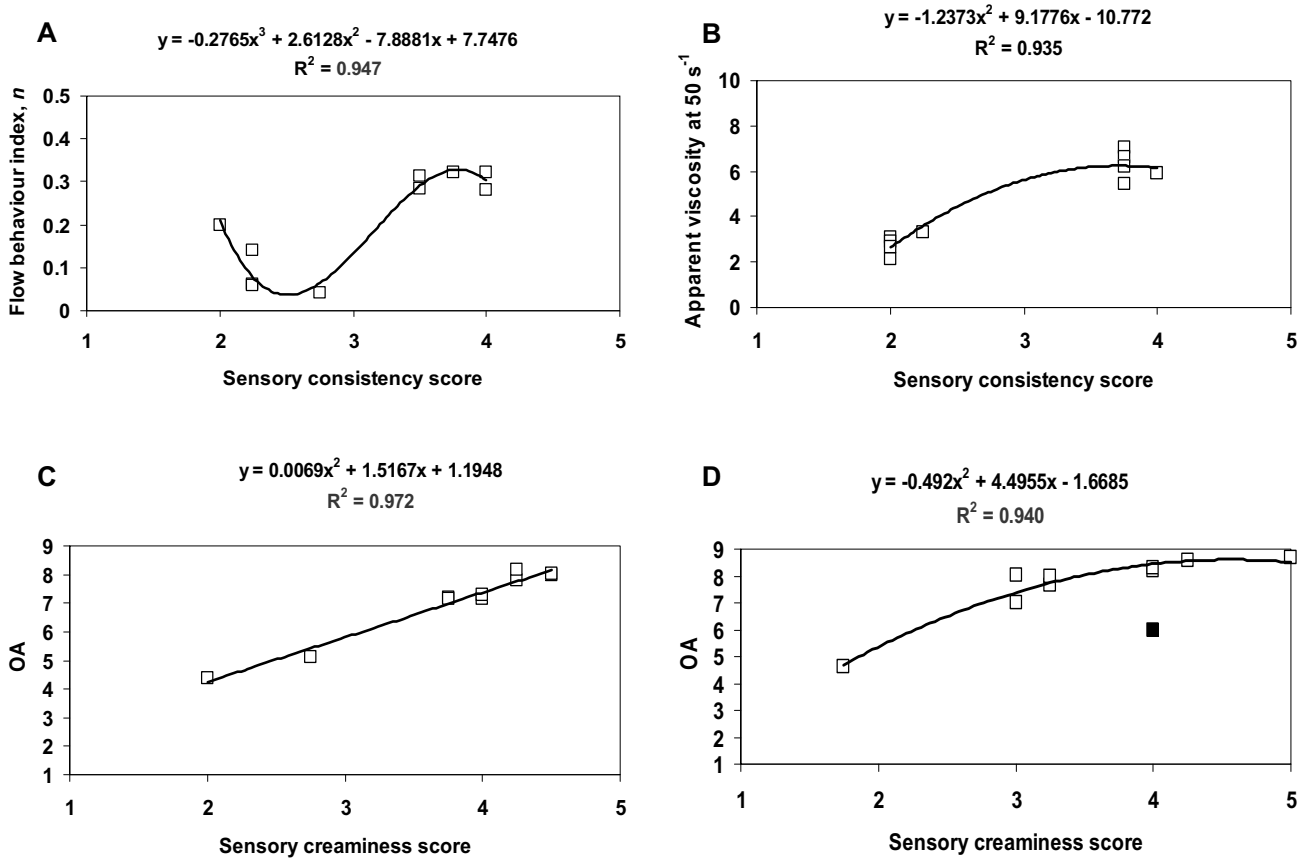

Fig. 7 Correlations between rheological properties and sensory texture attributes: (**A**) flow behaviour index by rheological measurement versus consistency measured by sensory evaluation in FMP samples; (**B**) Overall acceptability versus creaminess measured by sensory evaluation in FMP samples; (**C**) Apparent viscosity by rheological measurement versus consistency by sensory evaluation in F/TMP samples; (**D**) Overall acceptability versus creaminess measured by sensory evaluation in F/TMP samples.

either an aromatic or a creamy note detected in the oil-added MP (**Figs. 6A, 6B**). Certainly, samples with higher percentages of EVOO produced less sensations of dryness and roughness, more sensations of flavour, and more sensations of creamy and fatty mouth- and after-feel than the samples without added oil. Fat is a well-known enhancer of creaminess sensations (de Wijk *et al*. 2003). In vanilla custard desserts, the latter authors suggested that the possible mechanism by which fat affects the sensory attributes that are part of a rough-creamy/soft dimension include lubrication and flavour release. The effects of fat on odour and flavour attributes may be related to the flavour-releasing properties of fat. In sixteen virgin olives oils, volatile and phenolic compounds have been related to olfactory and gustative notes respectively (Cerretani *et al*. 2008). The volatile composition evidenced several correlations with olfactory attributes perceived by sensory analysis: the sum of aldehydes C_6 was correlated with orthosonal perception of olive fruity and retrosanal odour of almond. On the other hand, the effect of oil content on mayonnaise flavour was non-significant (Štern *et al*. 2007), although the authors ascribed this fact to the narrow range of oil used in that study.

Similarly, except in FMP samples containing 10 and 25 g kg^{-1} added EVOO panellists gave higher OA scores to the MPB samples (**Figs. 6C, 6D**). This is probably related to the presence of XG in the systems. In previous studies it was found that samples containing 0.5 and 1.5 g kg^{-1} added XG alone (Alvarez *et al*. 2008), and samples containing blends of κ-C and XG (each biopolymer at 1.5 g kg^{-1}) (Alvarez *et al*. 2009a; Fernández *et al*. 2009), were preferred organoleptically due to the creamy mouthfeel they produced. In these studies, κ-C appeared to provoke perceptions of melting/thickness, whereas XG provoked perceptions of roughness/creaminess/ softness. The effects of XG on mouth texture may be related to its WHC as perceived by the panellists. Finally, note that in the F/TMPB samples there were no significant differences between the OA scores given to the MP at any concentration of added EVOO (which were the highest) (**Fig. 6D**).

A complete dependence study was performed on the rheological properties versus texture scores obtained by sensory evaluation. Very good correlations with sensory consistency scores were found in the cases of pseudo-plasticity in the FMP samples (r^2 = 0.947) and of $\eta_{app,50}$ in the F/TMP ones (r^2 = 0.935) (**Fig. 7A, 7B**), respectively. Again, a quite good correlation was also found between consistency index (K) and sensory consistency score in the F/TMP samples (r^2 = 0.884, plot not shown). This means that n and $\eta_{app,50}$ affect sensory texture evaluation in both FMP and F/TMP products, respectively independently of all the other rheological properties. On the other hand, the OA scores of the FMP and F/TMP samples correlated very well with sensory creaminess scores (**Figs. 7C, 7D**). As can be seen in **Fig. 3D**, F/TMPB0 control has been represented by a filled square that was excluded from the statistical fit. The type of dependence between these two scores shows that panellists prefer MP with high creaminess. Therefore, creaminess also had a decisive influence on the OA score awarded to the FMP and F/TMP products.

CONCLUSIONS

The addition of either EVOO or cryoprotectants and the processing significantly affected the rheological, physical and sensory characteristics of MP, although the effect of EVOO concentration on the characteristics studied depended not only on the presence of cryoprotectants, but also on freezing/thawing. Adding 25 and 50 g kg^{-1} of EVOO (either before or after cooking) significantly reduced consistency and yield stresses and increased flow behaviour index and Casson plastic viscosity due to the coating properties and

the lubricant effect caused by the oil. The moment of addition of the highest EVOO concentration had a significant effect on some rheological properties, although panellists did not perceived these differences. Increased EVOO concentration resulted in enhancement of colour due to an increase in overall light scattering and pigment content. E_w values confirmed that the addition κ-C and XG (each hydrocolloid at 1.5 g kg^{-1}) was effective in stabilizing MP against syneresis, whereas EVOO by itself did not enhance the WHC of MP. Addition of κ-C and XG improved solidness, possibly through the exclusion effect of swollen starch granules promoting gelation of the κ-C. Freezing and thawing led to a less or a more structured system than in FMP counterparts depending respectively on whether κ-C and XG were absent or present. Addition of EVOO in increasing concentrations enhanced the sensory quality of MP in terms of increased creaminess and OA. Creaminess was the most crucial factor for OA of the products and was conferred either by EVOO or XG, which is linked to the lubricant properties of fat and to the presence of XG-water interactions and XG-amylose interactions that prevent retrogradation. Samples with 50 g kg^{-1} added EVOO were judged the best of all. Results indicate that in the presence of κ-C and XG, if the EVOO content is reduced to below 25 g kg^{-1}, the OA score for the product does not decrease, and hence its consumer acceptability is not adversely affected. This fact has important consequences for the formulation of EVOO-based MP, emphasizing on the development of reduced-fat foods that have the same desirable quality attributes as the original product.

ACKNOWLEDGEMENTS

The authors wish to thank the Spanish Ministry of Science and Innovation for financial support (AGL2007-62851).

REFERENCES

Adams MJ, Bedford LV, Geering J (1981) *QAV – a Method for the Sensory Appraisal of Quality Processed Vegetable Varieties. Technical Memorandum 278*. The Campden Food Preservation Research Association, Chipping, Campden, Gloucestershire, UK, pp 7-29

Alvarez MD, Fernández C, Canet W (2004) Rheological behaviour of fresh and frozen potato puree in steady and dynamic shear at different temperatures. *European Food Research and Technology* **218**, 544-553

Alvarez MD, Canet W, Fernández C (2005) Effect of freezing/thawing conditions and long-term frozen storage on the quality of mashed potatoes. *Journal of the Science of Food and Agriculture* **85**, 2327-2340

Alvarez MD, Canet W, Fernández, C (2008) Effect of addition of biopolymers on the mechanical properties, colour and sensory attributes of fresh and frozen/thawed mashed potatoes. *European Food Research and Technology* **226**, 1525-1544

Alvarez MD, Fernández C, Canet W (2009a) Enhancement of freezing stability in mashed potatoes by the incorporation of kappa-carrageenan and xanthan gum blends. *Journal of the Science of Food and Agriculture* **89**, 2115-2127

Alvarez MD, Fernández C, Canet W (2009b) Oscillatory properties of fresh and frozen/thawed mashed potatoes as modified by mixtures of amidated low-methoxyl pectin and xanthan gum. In: Yee N, Bussel WT (Eds) Potato IV. *Food* **3 (Special Issue 2)**, 55-65

Arocas A, Sanz T, Fiszman SM (2009) Improving effect of xanthan and locust bean gums on the freeze-thaw stability of white sauces made with different native starches. *Food Hydrocolloids* **23**, 2478-2484

Ayuso J, Haro MR, Escolar D (2004) Simulation of the visible spectra for edible virgin oils: Potential uses. *Applied Spectroscopy* **7**, 474-480

Bagley EG, Christianson DD (1982) Swelling capacity pf starch and its relationship to suspension viscosity: Effect of cooking time, temperature and concentration. *Journal of Texture Studies* **13**, 115-126

Baixauli R, Salvador A, Fiszman SM, Calvo C (2002) Effect of the addition of corn flour and colorants on the colour of fried, battered squid rings. *European Food Research and Technology* **215**, 457-461

Baixauli R, Sanz, T, Salvador A, Fiszman SM (2004) Effect of the addition of dextrin or dried egg on the rheological properties of batters for fried foods. *Food Hydrocolloids* **17**, 305-310

Baranowska HM, Sikora M, Kowalski S, Tomasik P (2008) Interactions of potato starch with selected polysaccharide hydrocolloids as measured by low-field NMR. *Food Hydrocolloids* **22**, 336-345

BeMiller JN, Whistler RL (1996) Carbohydrates. In: Fennema OR (Ed) *Food Chemistry* (3rd Edn), Marcel Dekker: NY, pp 157-224

Bendini A, Cerretani L, Carrasco-Pancorbo A, Gómez-Caravaca AA, Segura-Carretero A, Fernández-Gutiérrez A, Lercker G (2007) Phenolic molecules in virgin olive oils: a survey of their sensory properties, health effects, antioxidant activity and analytical methods. An overview of the last decade. *Molecules* **12**, 1679-1719

Bistany KL, Kokini JL (1983) Dynamic viscoelastic properties of foods in texture control. *Journal of Rheology* **27**, 605-620

Bolliger S, Wildmoser H, Goff HD, Tharp BW (2000) Relationship between ice cream mix viscoelasticity and ice crystal growth in ice cream. *International Dairy Journal* **10**, 791-797

Bourne MC (2002) *Food Texture and Viscosity*: *Concept and Measurement*, Academic Press, NY, 78 pp

Canet W, Alvarez MD, Fernández C, Luna P (2005a) Comparisons of methods for measuring yield stresses in potato puree: Effect of temperature and freezing. *Journal of Food Engineering* **68**, 143-153

Canet W, Alvarez MD, Fernández C, Tortosa ME (2005b) The effect of sample temperature on instrumental and sensory properties of mashed potato products. *International Journal of Food Science and Technology* **40**, 481-493

Cavella S, Di Monaco R, Torrieri E, Masi P (2009) Structure of a new functional walnut oil-enriched mayonnaise. Icheap-9: 9th International Conference on Chemical and Progress Engineering, pts 1-3. *Chemical Engineering Transactions* **17**, 879-884

Cerretani L, Salvador MD, Bendini A, Fregapane G (2008) Relationship between sensory evaluation performed by Italian and Spanish official panels and volatile and phenolic profiles of virgin olive oils. *Chemosensory Perception* **1**, 258-267

Chantrapornchai W, Clydesdale F, McClements DJ (1999) Influence of droplet characteristics on the optical properties of colored oil-in-water emulsions. *Colloids and Surfaces A* **155**, 373-382

Criado MN, Romero MP, Casanovas M, Motilva MJ (2008) Pigment profile and colour of monovarietal virgin olive oils from Arbequina cultivar obtained during two consecutive crop seasons. *Food Chemistry* **110**, 873-880

de Wijk RA, van Gemert LJ, Terpstra MEJ, Wilkison CL (2003) Texture of semi-solids; sensory and instrumental measurements on vanilla custard desserts. *Food Quality and Preference* **14**, 305-317

Dickinson E, Chen JS (1999) Heat-set whey protein emulsion gels: Role of active and inactive filler particles. *Journal of Dispersion Science and Technology* **20**, 197-213

Eliasson AC, Kim HR (1992) Changes in rheological properties of hydroxylpropyl potato starch pastes during freeze-thaw treatments I. A rheological approach for evaluation of freeze-thaw stability. *Journal of Texture Studies* **23**, 279-295

Escolar D, Haro MR, Ayuso J (2007) The color space of foods: Virgin olive oil. *Journal of Agricultural and Food Chemistry* **55**, 2085-2093

Fernández C, Alvarez MD, Canet W (2006) The effect of low-temperature blanching on the quality of fresh and frozen/thawed mashed potatoes. *International Journal of Food Science and Technology* **41**, 577-595

Fernández C, Alvarez MD, Canet W (2008) Steady shear and yield stress of fresh and frozen/thawed mashed potatoes: Effect of biopolymers addition. *Food Hydrocolloids* **22**, 1381-1395

Fernández C, Canet W, Alvarez MD (2009) Quality of mashed potatoes: effect of adding blends of kappa-carrageenan and xanthan gum. *European Food Research and Technology* **229**, 205-222

Ferrero C, Martino MN, Zaritzky NE (1993) Stability of frozen starch pastes: effect of freezing, storage and xanthan gum addition. *Journal of Food Processing and Preservation* **17**, 191-211

Ferrero C, Martino MN, Zaritzky NE (1994) Corn starch–xanthan gum interaction and its effect on the stability during storage of frozen gelatinized suspensions. *Starch* **46 (8)**, 300-308

Ferrero C, Zaritzky NE (2000) Effect of freezing rate and frozen storage on starch-sucrose-hydrocolloid systems. *Journal of the Science of Food and Agriculture* **80**, 2149-2158

Ford LD, Borwankar R, Martín RW Jr., Holcomb DN (1997) Dressings and sauces. In SE Friberg, K Larsson (Eds) *Food Emulsions*, Marcel Dekker, NY, pp 361-412

Giannouli P, Morris ER (2003) Cryogelation of xanthan. *Food Hydrocolloids* **17**, 495-501

Holdsworth, SD (1971) Applicability of rheological models to the interpretation of flow and processing behavior of fluid food products. *Journal of Texture Studies* **2**, 393-396

Juszack L, Fortuna T, Kosla A (2003) Sensory and rheological properties of Polish commercial mayonnaises. *Nahrung* **47**, 232-235

Kim HR, Eliasson AC (1993) Changes in rheological properties of hydroxylpropyl potato starch pastes during freeze-thaw treatments II. Effect of molar substitution and cross-linking. *Journal of Texture Studies* **24**, 199-213

Kim HR, Muhrbeck P, Eliasson AC (1993) Changes in rheological properties of hydroxypropyl potato starch pastes during freeze-thaw treatments III. Effect of cooking conditions and concentration of the starch paste. *Journal of the Science of Food and Agriculture* **61**, 109-116

Lee MH, Baek MH, Cha DS, Park HJ, Lim ST (2002) Freeze–thaw stabilization of sweet potato starch gel by polysaccharide gums. *Food Hydrocolloids* **16**, 345-352

Liehr M, Kuliche WM (1996) Rheological examination of the influence of

hydrocolloids on the freeze-thaw-stability of starch gels. *Starke (Weinheim)* **48**, 52-57

Mandala IG, Palogou ED (2003) Effect of preparation conditions and starch/ xanthan concentration on gelation process of potato starch systems. *International Journal of Food Properties* **6 (2)**, 311-328

Mandala IG, Savvas TP, Kostaropoulos AE (2004) Xanthan and locust bean gum influence on the rheology and structure of a white model-sauce. *Journal of Food Engineering* **64**, 335-342

Nourian F, Ramaswamy HS, Kushalappa AC (2003) Kinetics of quality change associated with potatoes stored at different temperatures. *Lebensmittel Wissenschaft und Technologie* **36**, 49-65

O'Mahony M (1986) Additional nonparametric tests. In: Tannenbaum SR, Walstra P (Eds) *Statistical Methods and Procedures*, Marcel Dekker, NY, pp 303-365

Paraskevopoulou A, Boskou D, Kiosseoglou V (2005) Stabilization of olive oil- lemon juice emulsion with polysaccharides. *Food Chemistry* **90**, 627-634

Parker A, Gunning PA, Ng K, Robins MM (1995) How does xanthan stabilise salad dressing? *Food Hydrocolloids* **9**, 333–342

Pérez-Jiménez F (2005) International conference on the healthy effect of virgin olive oil. *European Journal of Clinical Investigation* **35**, 421-424

Rao MA (1999) Flow and functional models for rheological properties of fluid foods. In: Barbosa-Cánovas GV (Ed) *Rheology of Fluid and Semisolid Foods. Principles and Applications*, Aspen Publishers, Inc., Gaithersburg, MD, pp 25-59

Rodd AB, Davis CR, Dunstan DE, Forrest BA, Boger DV (2000) Rheological characterisation of 'weak gel' carrageenan stabilised milks. *Food Hydrocolloids* **14**, 445-454

Severini C, De Pilli T, Baiano A (2003) Partial substitution of pork backfat with extra-virgin olive oil in 'salami' products: Effects on chemical, physical and sensorial quality. *Meat Science* **64**, 323-331

Stark AH, Madar Z (2002) Olive oil as a functional food: Epidemiology and nutritional approaches. *Nutrition Reviews* **60**, 170-176

Štern P, Míková K, Pokorný J, Valentová H (2007) Effect of oil content on the rheological and textural properties of mayonnaise. *Journal of Food and Nutrition Research* **46**, 1-8

Sun C, Gunasekaran S (2009) Effects of protein concentration and oil-phase volume fraction on the stability and rheology of menhaden oil-in-water emulsions stabilized by whey protein isolate with xanthan gum. *Food Hydrocolloids* **23**, 165-174

Sych J, Lacroix C, Adambounou LT, Castaigne F (1990) Cryoprotective effect of lactitol, palatinit and polydextrose on cod surimi proteins during frozen storage. *Journal of Food Science* **55**, 356-360

Tárrega A, Costell E (2006) Effect of inulin addition on rheological and sensory properties of fat-free starch-based dairy desserts. *International Dairy Journal* **16**, 1104-1112

Tárrega A, Costell E, Rao MA (2006) Vane yield stress of native and cross-linked starch dispersions in skimmed milk: Effect of starch concentration and lambda-carrageenan addition. *Food Science and Technology International* **12**, 253-260

Whybrow S, Harrison CLS, Mayer C, Stubbs RJ (2006) Effects of added fruits and vegetables on dietary intakes and body weight in Scottish adults. *British Journal of Nutrition* **95**, 496-503

Windhab EJ (1995) Rheology in food processing. In: Beckett ST (Ed) *Physico-chemical Aspects of Food Processing*, Blackie, UK, pp 80-116