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Inulin as texture modifier in dairy products

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ABSTRACT

In this review we will describe the application of inulin for texture improvement in a variety of dairy applications as this is one of the most important application areas. The effects of inulin in these systems as a fat replacer, i.e. how it can be used to mimic the features of fat for mouthfeel and creaminess, and how these effects may be related to changes in rheology of the food system will be described for liquid, semi-solid and solid dairy products.

1. Introduction

Inulin is a carbohydrate built up from β(2,1)-linked fructosyl residues mostly ending with a glucose residue and it is present as storage carbohydrate in a large number of plants (van Loo, Coussement, de Leenheer, Hoebregs, & Smits, 1995; Ritsema & Smeekens, 2003). It can for instance be found in onions (1–5% on a fresh weight basis), garlic (4–12%), banana (0.2%) and chicory roots (15–20%). Native or medium chain length inulin as it is present in chicory has a degree of polymerisation (DP) ranging from 3 to 60 monosaccharide units with an average of about 10; its partial enzymatic hydrolysis product is called oligofructose (OF) that has a DP ranging from 2 to 8 with an average of about 4. Long-chain inulin with average DP of about 23 and a DP ranging from 10 to 60 can be produced from native inulin by applying specific separation techniques.

Chicory is used mainly as the raw material for industrial production of inulin as a food ingredient (Boeckner, Schnepf, & Tungland, 2000). The production started in the early 1990s in Belgium and the Netherlands and the production volume has been growing ever since. This non-digestible carbohydrate is now employed in an increasing number of applications across the food market; it can for instance be found in dairy and bakery products, in beverages, in cereals and cereal bars, in low-fat spreads, in ice cream and in confectionary products (Franck, 2000; Meyer, De Wolf, & Olivier, 2007). Next to these food applications inulin also finds use in non-food applications as a filler/binder in tablets (Eissens, Bolhuis, Hinrichs, & Frijlink, 2002), and in pet food and feed (Van Loo, 2007). Chemical derivatives of inulin are used in industrial applications (for a review see Stevens, Meriggi, & Booten, 2001); for instance, carboxymethyl inulin is used as anti-scaling agent in waste water treatment (Martinod, Neville, Euvrad, & Sorbie, 2009).

The extensive use in food industry is based on the nutritional and technological properties of inulin. For the former not only the dietary fibre properties of inulin are important (such as the positive effect on bowel habit, Tungland & Meyer, 2002) but also the prebiotic properties. These arise from the fact that inulin can cause a specific shift in the composition of the colonic microbiota that has beneficial effects for the human host (Gibson, Probert, van Loo, Rastall, & Roberfroid, 2004). This specific increase in bifidobacteria (the so-called bifidogenic effect) is found in humans of all ages (Meyer & Stasse-Wolthuis, 2009) and it is linked to a variety of beneficial physiological effects. These include improved bowel habits (Marteau et al., 2011), increased calcium absorption with positive effects for bone health (Meyer & Stasse-Wolthuis, 2006), a lowering of serum lipids with relevance for heart health (Brighenti, 2007), a positive effect on feeling of satiety with potential positive consequences for weight management (Cani, Joly, Horsmans, & Delzenne, 2006; Parnell & Reimer, 2009) and a potential effect to enhance resistance to infections (Cummings, Christie, & Cole, 2001) and to stimulate the immune system (Lomax & Calder, 2009).

The technological use of inulin is based on its properties as a sugar replacer (especially in combination with high intensity sweeteners), as a fat replacer and texture modifier. For fat replacement in low-fat dairy products inulin seems particularly suitable as it may contribute

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to an improved mouthfeel. Guggisberg, Cuthbert-Steven, Piccinah, Buetikofer, and Eberhard (2009), Guven, Yasar, Karaca, and Hayaloglu (2005), Kip, Meyer, and Jellema (2006) and Paseephol, Small, and Sherkat (2008) showed that especially long-chain inulin addition to low-fat yoghurt resulted in enhanced creaminess. Others showed that this effect also occurs in low-fat cheese (Hennelly, Dunne, O'Sullivan, & O'Riordan, 2006; Koca & Metin, 2004; Pagliarini & Beatrice, 1994), in yoghurt ice cream (El-Nagar, Glowers, Tudorica, & Kuri, 2002), in chocolate mousse (Cardarelli, Buriti, de Castro, & Saad, 2008b) and in custards (Tárrega & Costell, 2006b; González-Tomás, Bayarri, & Costell, 2009b). When inulin is added to food in low concentrations the rheological properties and the sensory quality of the product will not be affected strongly due to the neutral or slightly sweet taste and the limited effect on viscosity of this ingredient (Franck, 2002; Kalyani Nair, Kharb, & Thompkinson, 2010). However, to make inulin-based dietary fibre claims inulin should be added in amounts that range from 3 to 6 g 100 g or 100 ml (European Parliament, 2006) and contents of 3–8 g per portion have to be added in order to assure its bifidogenic effect (Coussement, 1999; Meyer & Stasse-Wolthuis, 2009). As inulin content increases its effect on product structure and texture becomes important, because at these higher levels and due to its physico-chemical properties inulin can modify the texture of dairy products and may significantly influence their sensory quality (Tungland & Meyer, 2002).

The physico-chemical properties of inulin are linked to the degree of polymerisation. The short-chain fraction, oligofructose, is much more soluble and sweeter than native and long-chain inulin, and can contribute to improve mouthfeel because its properties are closely related to those of other sugars. Long-chain inulin is less soluble and more viscous than the native product (Wada, Sugatani, Terada, Ohguchi, & Miwa, 2005), and can act as texture modifier (Coussement, 1999; Voragen, 1998). Other physico-chemical properties that are influenced by DP include the melting (Blecker et al., 2003; De Gennaro, Birch, Parke, & Stancher, 2000) and glass transition temperature (Schaller-Povolny, Smith, & Labuza, 2000), the capability for gel formation and the subsequent gel strength (Bot, Erle, Vreeker, & Agterof, 2004; Hébette et al., 1998; Meyer & Blaauwhoed, 2009) and the interaction with other food components such as starch or hydrocolloids (Bishay, 1998; Zimeri & Kokini, 2003a; Giannouli, Richardson, & Morris, 2004). Evidently, these features are also relevant for the technical applications of inulin especially for its use to modify and improve texture.

In connection with the current rise in obesity there is a strong demand to food industry to develop good tasting low caloric food products. Lowering the fat (or sugar) content of a food product is thus a relevant way forward for product development. However, the elimination or reduction of fat in foodstuffs not only modifies composition and structure but also the interactions among the various constituents, giving rise to clearly perceptible changes in colour, flavour, and texture (Bayarri & Costell, 2009), and possibly to less acceptable products. To solve some of the problems associated with fat reduction or elimination, one of the most frequent strategies is the use of fat replacers or fat mimetics to compensate for the shortcomings in texture (Sandrou & Arvantoyannis, 2000). With this type of ingredients it is possible, though not always easy, to mimic the rheology of full-fat products. However, this does not guarantee matching the texture in terms of creaminess etc. (Szczesniak, 2002). Although, generally speaking, mechanical and rheological properties are the predominant stimuli affecting texture perception in most foods, other attributes especially those related to surface and structure characteristics play a definitive role in the perceived texture of certain products (Foegeding, Çakir, & Koc, 2010; Nishinari, 2004; Wilkinson, Dijksterhuis, & Minekus, 2000). In dairy products, apart from thickness or hardness, attributes such as creaminess, fattiness or smoothness are also important for mouthfeel (De Wijk, Terpstra, Janssen, & Prinz, 2006; Elmore, Heymann, Johnson, & Hewett, 1999; González-Tomás & Costell, 2006; Weenen, Jellema, & De Wijk, 2005). Differences in rheological parameters might be able to explain the differences in thickness or hardness, but the relationship of texture properties such as creaminess, roughness or smoothness with rheological properties is much less clear.

In this review we will describe the application of inulin for texture improvement in a variety of dairy applications as this is one of the most important application areas. The effects of inulin in these systems as a fat replacer, i.e. how it can be used to mimic the features of fat for mouthfeel and creaminess, and how these effects may be related to changes in rheology of the food system will be described for liquid, semi-solid and solid dairy products.

2. Influence of inulin on rheology and texture of dairy products

2.1. Effect of inulin in liquid products

In Table 1 an overview of the variables used in studies of the effects of inulin addition of various dairy beverages is presented. De Castro, Cunha, Barreto, Camboni, and Prudêncio (2009) observed that the incorporation of 2% or 5% of oligofructose in whole fat fermented milk lowered the time dependency, the pseudoplastic behaviour and the consistency index value. No significant differences were detected in the flow behaviour of fermented milks with 2% or 5% of oligofructose. The authors suggested that the results may be related to a possible plasticising effect of oligofructose which results in less moisturising and reduction of the hydrodynamic volume of the protein, thereby decreasing viscosity.

When native or long-chain inulin was added to low-fat fermented milk or to kefir a different effect was observed. Native

Table 1
Overview of studies of the addition of different types of inulin on rheological and texture variables of liquid dairy products.

Product	Milk type	Inulin type[a]	Inulin conc. (%)	Rheology/Mechanical properties	Texture sensory data	Reference
Fermented milk	Whole	SC	2, 5	Flow behaviour	Preference, Acceptability	De Castro et al., 2009
	Skimmed	N	1, 2, 4	Puncture test	ND	Pinheiro et al., 2009
	Skimmed	LC	5	Flow behaviour	ND	Debon et al., 2010
Milk beverage	Whole, Skimmed	SC, N, LC	2–10	Flow behaviour	ND	Villegas & Costell, 2007
	Whole, skimmed	SC, N, LC	6, 8,10	Flow behaviour Apparent viscosity	Ranking test, R-index	Villegas et al., 2007
Kefir	Whole (cow and goat)	LC	2	Flow behaviour	ND	Tratnik et al., 2006
		ND	2	Flow behaviour Apparent viscosity	Descriptive profile	Ertekin & Guzel-Seydim, 2010

N, Native or medium chain inulin (average degree of polymerisation about 10); LC, Long-chain inulin (average degree of polymerisation 22–25); ND: No data.
[a] SC, Short-chain inulin or oligofructose (average degree of polymerisation about 4).

inulin at 2% and 4% increased firmness of milk fermented by *Streptococcus thermophilus* in co-culture with different *Lactobacillus* spp. or with *Bifidobacterium lactis* (Pinheiro, Pergo, Converti, & Nogueira, 2009). The addition of 5% long-chain inulin to low-fat fermented milk did not affect significantly the pseudoplasticity nor the consistency index values, but it did increase the flow time dependency and also increased significantly the apparent viscosity values below 50 s^{-1}. This shear rate is considered to represent the in-mouth shear as perceived on the palate (Debon, Prudencio, & Petrus, 2010). The observed variations of the flow behaviour of fermented milk with inulin could be explained by different factors: the capacity of inulin to retain water (Soukoulis, Lebesi, & Tzia, 2009); the interaction of inulin with milk protein that can lead to an increase in the molar mass which results in an increase in viscosity (Schaller-Povolny & Smith, 2001); the formation of small aggregates of microcrystals that are able to retain water (Gonzalez-Tomás, Coll-Marqués, & Costell, 2008) or by a greater total solids content. Along the same line, Tratnik, Bozanic, Herceg, and Drglic (2006) reported that kefir obtained from goat's or cow's milk supplemented with 2% inulin was also more viscous than the corresponding control sample. Villegas and Costell (2007) studied the effects of the addition of different types of inulin (short chain, native and long chain) at different concentrations (2–10%) on the flow behaviour of milk beverage model systems with different fat content in the absence or presence of κ-carrageenan. For low-fat milk samples with lower inulin concentrations (up to 6%) the flow showed Newtonian behaviour and no significant differences in viscosity among the three types of inulin were observed. These samples showed flow behaviour typical of dilute solutions with solute concentrations below the critical one, at which entanglement or aggregation between polymer chains begins (Kim, Faqih, & Wang, 2001). This behaviour is similar to that observed by Bishay (1998) and by Zimeri and Kokini (2003a) in aqueous inulin solutions at concentrations lower than 20%. With higher inulin concentrations (8 and 10%), a shear-thinning flow behaviour was observed and a sharp increase in apparent viscosity of samples with long-chain inulin was detected. Such changes in flow behaviour are often associated with structural changes in a product (Morris, 1995). In these products, this change of flow behaviour suggests the formation of a weak structure that can be due to an incipient formation of inulin aggregates. These aggregates would contain inulin crystals with significant amounts of entrapped fluid phase leading to an increase of the volume fraction of the dispersed phase (Bot et al., 2004). The aggregates can be relatively strong at low shear rates but they can be easily disrupted by shearing (Bishay, 1998). For whole-milk samples and for both short chain and native inulins the viscosity values increased slightly with concentration, while for long-chain inulin there was a rapid increase in viscosity at concentrations over 6%. The effect of an increase in inulin concentration on viscosity of the κ-carrageenan-whole-milk samples was less evident than in the inulin-whole-milk samples without κ-carrageenan. It seems that the flow behaviour of samples with κ-carrageenan is governed by the structure formed between the κ-carrageenan molecules and the casein micelles without evidence of a contribution from inulin aggregates. Probably in these systems inulin behaves only as a cosolute with the ability to bind water molecules, thus increasing the solution viscosity.

Villegas and Costell (2007) showed that the viscosity of whole-milk vanilla beverages could be approximated by skim milk beverages with 4–10% short-chain inulin, with 6–8% native inulin or with 4–6% long-chain inulin. These data show again that long-chain inulin is a more effective viscosifier in this system. Perceptible differences in thickness and creaminess between whole-milk and skimmed-milk vanilla beverage samples with different types of inulin were found by Villegas, Carbonell, and Costell (2007). Independent of the degree of polymerisation, when a concentration of 6% inulin was added to skimmed-milk, the milk beverages were perceived as less viscous and less creamy than the whole-milk sample. With a concentration of 8%, the three samples with different types of inulin were again perceived as less viscous than the whole-milk sample; however, the samples with long-chain or short-chain inulin did not differ in creaminess from the whole-milk sample. The sample with 10% of long-chain inulin had an apparent viscosity that did not differ significantly from the viscosity of whole-milk sample and was perceived as creamier.

Using a new approach based on tribological measurements Meyer, Vermulst, Tromp, and de Hoog (2011) determined the effect of inulin addition on the texture of various types of milk. The effects of the addition of long or medium chain length inulin (1, 3, or 5%) on the friction coefficient and sensory profile of skimmed-milk were assessed. Tribological analysis showed that with inulin the friction coefficient of skimmed-milk could be decreased to the value of full-fat milk, with long-chain inulin being more effective than native inulin. The addition of inulin to skimmed-milk had minor effects on mouthfeel: only attributes related to oral friction tended to be lower. Correlation analysis of the sensory and tribology data did not give a significant relationship. For milk with different fat contents trends for this correlation were observed: a decrease in friction (due to a lowered fat content) tended to correlate with an increase in the attribute 'creamy', whereas the friction related attribute 'thin as water' tended to be positively correlated with friction.

2.2. *Effect of inulin in semi-solid products*

A great number of semi-solid dairy products currently is available to consumers and yogurts and dairy desserts have been considered traditionally as healthy products, enjoyable and easy to eat, and with an attractive sensory quality. The health and technical benefits of inulin mentioned above combine well with these features and explain its application as functional ingredient in these types of products. Table 2 provides an overview of the studies about the effects of inulin in this type of dairy products.

Yogurt is a fermented dairy product with specific rheological and textural characteristics. The texture of yogurt is a result of the development of a three-dimensional network of milk proteins due to aggregation of casein micelles with denaturated whey proteins through hydrophobic and electrostatic bonds (Paseephol et al, 2008). Yogurt shows a time dependent and shear-thinning flow behaviour and the viscoelastic response of a weak gel. Dello Staffolo, Bertola, Martino, and Bevilacqua (2004) studied the effects of different dietary fibres (from apple, wheat, or bamboo and inulin) at a concentration of 1.3% on rheological and sensory properties of yogurts. No differences in apparent viscosity, maximum compression force, dynamic oscillatory parameters or texture acceptability were observed among yogurts fortified with wheat or bamboo fibre or inulin and the control yogurt without dietary fibre. Different results have been reported by Paseephol et al. (2008) who added inulins with different chain lengths at 4% concentration to non-fat yogurt. All inulin-containing yogurts in comparison with the control non-fat yogurt without inulin were characterised by lower values for firmness, apparent viscosity, yield stress, complex viscosity, and storage and loss modulus. The sample supplemented with long-chain inulin showed a rheological behaviour close to that of a control full-fat yogurt. The authors suggested that the softening effect of inulin on yogurt structure might be due to the lower protein content of inulin-enriched yogurt and also to the possibility that the inulin molecules were dispersed among the casein micelles thus interfering with the formation of the protein network. In contrast, Kip et al. (2006) found that the addition of inulins with different chain length at different

Table 2
Overview of studies of the addition of different types of inulin on rheological and texture variables of semi-solid dairy products.

Product	Milk type	Inulin type[a]	Inulin conc. (%)	Rheology/mechanical properties	Texture sensory data	Reference
Yogurt	Skimmed	SC	5	ND	Acceptability	Lin, 2003
	Whole	ND	1.3	Flow behaviour Viscoelasticity Extrusion test	Acceptability	Dello Staffolo et al., 2004
	Skimmed	N, LC	1.5, 3, 4	Apparent viscosity Posthumous funnel Puncture test	Descriptive profile	Kip et al., 2006
	Skimmed	SC, N, LC	1.5	Apparent viscosity	Quality test	Aryana et al., 2007
	Skimmed	SC, N, LC	4	Flow behaviour Viscoelasticity Puncture test	ND	Paseephol et al., 2008
	Skimmed, Whole	LC	1, 2, 4	Viscoelasticity Puncture test	Texture descriptive multiscale test	Guggisberg et al., 2009
	Skimmed	LC	1, 2, 3	Puncture test	Multiscale test	Guven et al., 2005
	Skimmed	LC	2, 4, 6	Apparent viscosity Viscoelasticity Back extrusion	Descriptive profile	Brennan & Tudorica, 2008
	Skimmed	LC	0.7, 2.7	Apparent viscosity	Quality test	Modzelewska-Kapitula & Klebukowska, 2009
Custard	Skimmed, Whole	LC	6	Viscosity profile Flow behaviour Viscoelasticity	Paired comparison test	Tárrega & Costell, 2006b
	Skimmed, Whole	SC, N, LC	2.5, 5, 7.5	Viscoelasticity	ND	Gonzalez-Tomas et al., 2008
	Skimmed, Whole	SC, N, LC	2.5, 5, 7.5	Flow behaviour	ND	González-Tomás, Bayarri, Coll-Marqués, et al., 2009a
	Skimmed	N	0.68–2.39	Instrumental texture profile	Free Choice Profile	Lobato et al., 2009
	Skimmed, Whole	SC, N, LC	7.5	Flow behaviour	Descriptive profile	González-Tomás, Bayarri, & Costell, 2009b
Mousse	Skimmed, Whole	N	5	Instrumental texture profile	Difference test	Cardarelli, Aragon-Alegro, et al., 2008a

N, Native or medium chain inulin (average degree of polymerisation about 10); LC, Long-chain inulin (average degree of polymerisation 22–25); ND: No data.
[a] SC, Short-chain inulin or oligofructose (average degree of polymerisation about 4).

concentrations (1.5%, 3%, and 4%) to low-fat yogurts increased the apparent viscosity and that the increase was higher when long-chain inulin was used. The most important effect of the addition of inulin to low-fat yogurt was on texture attributes that contribute to creamy mouthfeel. The samples with 3% long-chain inulin were perceived as most thick, airy, sticky and creamy. A similar study was carried out by Aryana, Plauche, Rao, McGrew, and Shah (2007). They studied the effect of three inulins with different chain lengths (short, medium and long) at 1.5% of concentration on fat-free yogurt. Inulin chain length did not have any significant effect on apparent viscosity, only the yogurt with long-chain inulin showed less syneresis than the control and the texture was evaluated as better with more body than the other yogurts. The effect of long-chain inulin addition (1%, 2% and 3%) and of fat content (from 0.1% to 3.5%) on rheology, resistance to penetration and on firmness, viscosity and creaminess of yogurt was also studied by Guggisberg et al. (2009). Inulin and fat significantly affected the rheological and sensory properties. The addition of up to 2% of inulin reduced syneresis and with increasing inulin concentration, higher yield stress, firmness and creaminess values were observed. Creaminess was significantly influenced by increasing inulin concentration in samples with 1%, 2% and 3,5% fat but no influence was observed in the samples containing only 0.1% fat. Thus it seems possible to use long-chain inulin in low-fat (2%) yogurts to improve rheological and sensory properties to the level of full-fat yogurt but this seems not possible in 0.2% fat yogurt even at 4% inulin (see also Kip et al., 2006).

Guven et al. (2005) investigated the possibility of using different concentrations (1%, 2% and 3%) of long-chain inulin as fat replacer in low-fat yogurt. Whey separation and consistency increased with inulin concentration and only the low-fat sample with the lower inulin concentration was similar to control yogurt made with whole-milk. With regard to mouthfeel, no significant differences were found in body and texture scores among all samples tested. In contrast, Brennan and Tudorica (2008) observed that levels above 2% of long-chain inulin were needed to exert significant improvements in apparent viscosity and storage modulus values and to obtain values closer to those of full-fat yogurt. Sensory analysis did not detect differences in the viscosity perceived but incorporation of 6% inulin significantly improved the creaminess, mouthfeel and smoothness in comparison with low-fat control yogurt. Similar results were obtained when a 2.7% long-chain inulin was added to low-fat yogurt. The apparent viscosity and the texture score increased but remained lower than that of full-fat yogurt (Modzelewska-Kapitula & Klebukowska, 2009).

Semi-solid dairy desserts are widely consumed in Europe (some examples are “Natillas” in Spain, “Vanilla vla” in The Netherlands or “Crème dessert” in France). They are basically formulated with milk, thickeners (starch or sodium carboxymethyl cellulose and other hydrocolloids), sucrose, aroma and colorants (Jellema, Janssen, Terpstra, de Wijk, & Smilde, 2005; Tárrega, Durán, & Costell, 2005). This type of products shows time dependent and shear-thinning flow behaviour, and viscoelastic properties typical of weak gels (Bayarri, Dolz, & Hernández, 2009b; Bayarri, González-Tomás, & Costell, 2009a; Doublier & Durand, 2008; Tárrega & Costell, 2006a). Tárrega and Costell (2006b) studied the effect of the addition of long-chain inulin (6%) to fat-free dairy desserts containing different starch concentrations (2.5%, 3.25% and 4%). For none of the starch concentrations significant differences were detected between inulin-skimmed-milk and whole-milk samples for the hysteresis loop areas. In skimmed-milk samples with 2.5% and 3.25% starch, inulin addition increased apparent viscosity, storage modulus and complex viscosity values and decreased loss tangent. For all of these parameters no significant differences between whole-milk and inulin-skimmed-milk samples were found. At the highest starch concentration, inulin did not increase storage modulus and complex viscosity values and in the whole-milk sample apparent viscosity, storage modulus and complex viscosity were higher than in inulin-skimmed-milk sample. Furthermore, addition of inulin to fat-free desserts resulted in a significant increase in thickness and creaminess except for samples with 4% starch concentration. Apparently the effects of 6% long-chain inulin on rheology and texture of starch-based dairy products were dependent on starch concentration due to the competition between inulin and starch for water.

The effect of the addition of different types of inulin (long-chain, native and short-chain inulin) at three concentrations (2.5%, 5% and 7.5%) on viscoelasticity and on flow behaviour of semi-solid dairy desserts prepared with either skimmed or whole-milk and three starch concentrations (2.5, 3.25 and 4% w/w) was studied by González-Tomás, Bayarri, Coll-Marqués, and Costell (2009a) and González-Tomás, Coll-Marqués, and Costell (2008). The effect of the different types of inulin on viscoelastic and flow properties of the systems not only was very much dependent on the starch concentration, but also on the inulin concentration. The fat content dampened the extent of the inulin effects as the change in the viscoelasticity and flow characteristics in low-fat samples due to inulin was less in whole-milk systems. The most pronounced effects were observed with the addition of 7.5% long-chain inulin: a significant increase of consistency index values and decrease of flow index and loss tangent values was observed with both types of milk and for all starch concentrations. Lobato, Grossmann, and Benassi (2009) analysed the effect of interactions among milk, starch and inulin of medium chain length on the instrumental texture profile parameters and on sensory characteristics of a milk pudding. Only milk and starch concentration showed a significant contribution to firmness, gumminess and adhesiveness, while inulin affected only the cohesiveness: with increasing inulin content cohesiveness decreased. This may be due to the fact that inulin weakens the starch network. González-Tomás et al. (2009b) studied how inulin of different average chain lengths (long-chain, native and short-chain inulin) at a concentration of 7.5% influences the physico-chemical and sensory characteristics of starch-based dairy desserts formulated with either skimmed or whole-milk. The skimmed-milk sample with long-chain inulin and the whole-milk sample without inulin showed similar flow behaviour. Both samples were perceived to have the same consistency intensity, but long-chain inulin addition increased roughness intensity in samples with both milk types and consequently its sensory quality was affected negatively. Based on the data of Hébette et al. (1998) and Kim et al. (2001) about the shape and particle size of inulin crystals in aqueous media, the authors suggested that the roughness could be due to the presence of small crystals or crystal aggregates of long-chain inulin in the product.

Mousses are an interesting type of dairy dessert with an aerated and stabilised foamy structure that can be a good vehicle for the incorporation of healthy ingredients. Cardarelli, Aragon-Alegro, Alegro, de Castro, and Saad (2008a) evaluated the effect of a probiotic (*Lactobacillus paracasei*) added together with inulin of medium chain length at 5% of concentration on instrumental texture and sensory attributes of a chocolate mousse. The synbiotic sample showed the highest value in instrumental firmness and adhesiveness and was perceived as significantly firmer than the other formulations studied (control and probiotic only).

2.3. *Effect of inulin in solid products*

The boundaries between liquid and semi-solid and between semi-solid and solid foods are not always evident. In any case soft dairy products as some cheeses and ice creams present clear structural and textural differences from yogurts, custard desserts and mousses. For this reason cheeses and ice creams in this paper are consider as "solid" dairy products (Table 3), although some of them, as cream cheeses, could be also considered as semi-solid products.

2.4. *Cheese products*

Cream and soft cheeses can be attractive carriers for probiotic bacteria and prebiotic ingredients to obtain synbiotic products (Buriti, Carderelli, Filisetti, & Saad, 2007). With this objective Cardarelli, Buriti, de Castro, and Saad (2008b) studied the possibility of producing a synbiotic *petit-suisse* cheese using two probiotic strains (*Lactobacillus acidophilus* and *Bifidobacterium animalis* subsp. *lactis*) and three prebiotics (medium chain inulin, short-chain inulin or oligofructose) at 10% concentration. After 28 days of refrigerated storage the highest sensory acceptance was observed for the samples with 10% oligofructose and the best synbiotic *petit-suisse* cheese, based on acceptance and functional features, was that containing oligofructose and medium chain inulin combined (50/50). Along the same line, Araujo, de Carvalho, Leandro, Furtado, and de Moraes (2010) developed a synbiotic cottage cheese with *Lactobacillus delbrueckii* UFV H2b20 and 8% medium chain inulin. The addition of

Table 3
Overview of studies of the addition of different types of inulin on rheological and texture variables of solid dairy products.

Product	Milk type	Inulin type[a]	Inulin conc. (%)	Rheology/mechanical properties	Texture sensory data	Reference
Cheese	Skimmed	N, LC	10	ND	Acceptability	Cardarelli, Buriti, et al., 2008b
	Skimmed	N	8	ND	Acceptability	Araujo et al., 2010
Fresh kashar cheese	Skimmed	LC	5	Instrumental texture profile	Acceptability	Koca & Metin, 2004
Imitation cheese	ND	LC	5, 13.75	Instrumental texture profile Viscoelasticity	ND	Hennelly et al., 2006
Ice cream	Skimmed	LC	3.3, 6.7	ND	Descriptive multiscale test	Schaller-Povolny & Smith, 1999
	Skimmed	LC	3.3, 6.7	Flow behaviour	ND	Schaller-Povolny & Smith, 2001
	Skimmed	N	5, 7, 9	Flow behaviour Puncture test	Texture descriptive multiscale test	El-Nagar et al., 2002
	Whole	ND	1, 2	Apparent viscosity	Quality test	Akin et al., 2007
	Whole	LC	2, 4	Flow behaviour	ND	Soukoulis et al., 2009
	Whole, skimmed	LC	4	Flow behaviour Puncture test	ND	Akalm, Karagözlü, & Ünal, 2008
	Skimmed	LC	4, 6, 8	Puncture test Flow behaviour	Quality test	Karaca et al., 2009

N, Native or medium chain inulin (average degree of polymerisation about 10); LC, Long-chain inulin (average degree of polymerisation 22–25); ND: No data.
[a] SC, Short-chain inulin or oligofructose (average degree of polymerisation about 4).

probiotic bacteria and inulin did not change taste or texture of the cottage cheese after 15 days of storage at 5 °C in comparison with the control non-probiotic cheese.

Hennelly et al. (2006) compared the use of shear-induced inulin gels and heated inulin solutions to replace 63% of the fat in imitation cheese. The melting behaviour and the variation of the elasticity modulus with temperature and the cheese microstructure were not affected by the form in which inulin was added (inulin gel or inulin solution). They also observed that at equivalent moisture levels, the inulin cheeses had significantly higher hardness values than the control sample with fat; however, there was no difference in hardness between the cheeses containing different levels of inulin (5% or 13.75%).

Koca and Metin (2004) studied the possibility to obtain low-fat fresh kashar cheese with a 70% fat reduction using long-chain inulin. First they showed that low-fat control cheese due to its high protein content was significantly harder, more elastic, gummier and chewier than the full-fat control cheese. The authors comment that it is not surprising because fat breaks the protein matrix and acts as lubricant to provide a softer texture. Addition of 5% inulin to the low-fat cheese resulted in a significantly lower hardness compared to low-fat control cheese but slightly higher than that of full-fat control cheese. According to these authors, the softening effect observed in the sample with inulin could be attributed to both the higher ratio of moisture to protein and to the increase in filler volume that results in a decrease in the amount of protein matrix. In general, inulin improved the cheese texture until the 30th day of storage but reduced its shelf life. The sensory scores of inulin cheese decreased due to softening and development of off-flavour on the 60th and 90th days of storage.

2.5. Ice cream

The quality of ice cream is related to physico-chemical attributes such as the size of ice crystals, viscosity, freezing point and to sensory attributes (hardness, creaminess, chewiness, melting, and flavour). Schaller-Povolny and Smith (1999, 2001) studied the effects of substitution of long-chain inulin for 42DE corn syrup on sensory attributes, flow behaviour and freezing point in a reduced fat ice cream. Inulin reduced the freezing point depression and altered the texture and rheology of the ice cream by increasing chewiness, flow consistency and pseudoplasticity. These changes in product quality might be due to a competition for water for hydration or interaction between inulin and milk proteins or both. The objective of the work of El-Nagar et al. (2002) was to examine the rheological, textural and sensory characteristics of low-fat yog-ice cream desserts (a 1/1 mixture of standard stirred yogurt with a liquid ice cream preparation) with medium chain inulin at different concentrations (5%, 7%, and 9%). Consistency index values and apparent viscosity increased and the rate of meltdown decreased with increasing inulin concentration. They suggested that inulin may act as a stabiliser due to its capacity for binding water; water molecules become immobilised and are unable to move freely among other molecules of the ice mix. Furthermore, inulin increased stickiness and lowered hardness and improved the textural characteristics although changes in inulin concentrations appeared not to affect the intensity of texture attributes. Akin, Akin, and Kirmaci (2007) also investigated the effects of inulin (1% and 2%) and sugar levels on some physical properties and on sensory quality of probiotic ice cream. The addition of inulin increased the complete melting time and viscosity, but had no effect on sensory perception of body and texture quality. Soukoulis et al. (2009) evaluated the effects of four dietary fibres (oat, wheat, apple and inulin) on flow behaviour, ice formation and glass transition on fibre-enriched ice creams. For inulin they showed an increase of viscosity with increasing inulin concentration from 2% to 4%. Differences in thixotropy amongst control and samples with inulin were not significant. Inulin caused also an increase of glass transition temperature indicating a reduction of water molecule mobility from the bulk aqueous phase to the ice crystal surface.

Karaca, Güven, Yasar, Kaya, and Kahyaoglu (2009) compared the effects of Simplesse® D-100 (protein-based), N-Lite D (starch-based) and long-chain inulin on rheological and sensory properties of reduced or low-fat and non-fat ice creams. Samples with 4% and 6% inulin have the same viscosity as the control sample and with 8% inulin a higher viscosity was obtained. Texture quality assessment showed that reduced and low-fat ice creams with fat replacers had scores similar to the control samples but non-fat samples had lower scores. Comparison of 4% inulin with 4% whey protein isolate as fat replacers in reduced fat and low-fat ice creams showed that with both hardness of low-fat ice cream significantly increased compared to the regular ice cream. Samples with inulin had viscosity and consistency coefficient values similar to the control sample, while samples containing whey protein isolate had a higher viscosity that resulted in an excess thickening of the ice cream.

3. Underlying mechanisms

As commented previously the property of long-chain inulin to act as fat mimetic or fat replacer is based on its capacity to form microcrystals, which interact with each other thereby forming small aggregates that ultimately may agglomerate into a gel network (Hébette et al., 1998). Thus, knowledge of the mechanisms of crystallisation and particles aggregation is important to understand the effect of inulin addition to low-fat products as fat replacer.

The degree of polymerisation of oligofructose or short-chain inulin is insufficient to form microcrystals. Only native and long-chain inulins in concentrate aqueous solutions can develop a gel structure formed by a network of crystalline particles (Chiavaro, Vittadini, & Corradini, 2007; Hébette et al., 1998). According to Hébette et al. (1998) only the longer chains with DP > 10 participate in the gel formation; the smaller chains remain dissolved. Initially, native and long-chain inulin form primary non-spherical crystals (0.5 by 3 μm) that aggregate including significant amounts of fluid phase, and afterwards the aggregates interact to form a gel.

Crystallisation rate, crystal size and gel firmness depend on inulin concentration, degree of polymerisation, shear treatment, thermal treatment and the presence of seed crystals (Bot et al., 2004; van Duynhoven, Kulik, Jonker, & Haverkamp, 1999; Kim et al., 2001; Meyer & Blaauwhoed, 2009). The effect of chain length and concentration on gel firmness is shown in Fig. 1. The longer chains have a lower solubility than the shorter ones and therefore they will crystallise more rapidly. Zimeri and Kokini (2003a) using light microscopy, observed the presence of some inulin crystals immersed in the continuous phase in water solutions of 5% long-chain inulin. They proposed that these crystals are the result of either insolubility or recrystallisation of long-chain inulin after cooling. It is to be expected that when other food ingredients are present, the inulin crystallisation process will be affected as these ingredients may influence crystallisation rate and crystal size. Hence the properties of the final gel structure will also be influenced and its rheological and sensory properties. However there is still very little information available for the inulin crystallisation phenomena in real food matrices. The descriptions above and below are based on data from model systems.

The rheological behaviour of inulin and inulin-hydrocolloid mixtures in water was characterised by Bishay (1998), who found a synergistic effect between inulin and calcium alginate and a negative interaction between inulin and starch probably because both of them have a high water affinity. Working on inulin-waxy

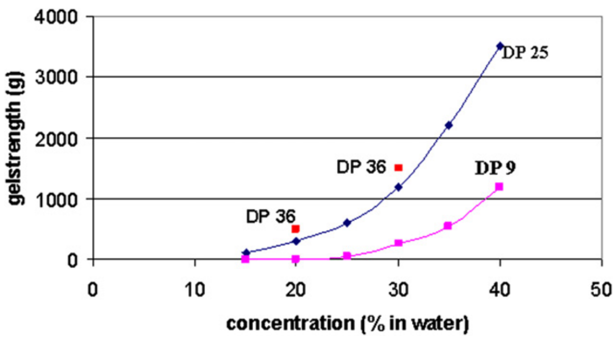

Fig. 1. Gel strength in relation to concentration of native inulin (DP 9), long-chain inulin (DP 25) from chicory roots and inulin from *Cynara scolymus* (DP 36). Inulin gels were prepared by dissolving inulin in the concentrations given in water of 85 °C and gels were allowed to form during overnight cooling (4 °C). Gel strength was measured with a Stevens Texture Analyser. (Figure reproduced from Meyer & Blaauwhoed, 2009 with permission by Woodhead Publishers Ltd.).

maize starch systems Zimeri and Kokini (2003a,b) found that a change in rheological behaviour when the sample structure changed from a starch-continuous system, with inulin as the dispersed phase, to an inulin-continuous system, with starch as the dispersed phase. In the systems in which inulin was the dispersed phase, starch, the more elastic component, embedded the inulin chains and the increase of the concentration of inulin produced non-gelled, liquid-like systems. They concluded that in these cases inulin interfered with the network formation of starch acting as a diluent. A different result was observed by Giannouli et al. (2004) studying the effect of the addition of different inulin concentrations (from 5 to 35%) on calcium pectinate gelation. When they analysed the changes in the storage (G') and loss (G'') moduli for 2.0% low methoxy pectin with different inulin concentrations on cooling from 90 to 5 °C, they found a progressive increase in G' and in G'' values at high temperature (70–90 °C) when increasing inulin concentration but not at 5 °C. They concluded that in these systems the rheological changes observed are swamped by gelation of calcium pectinate or that the presence of the pectin chains inhibits self-association of inulin.

When comparing the influence of inulin addition on viscosity of dairy beverages Villegas and Costell (2007) observed that the increase in viscosity with inulin concentration was lower in low-fat κ-carrageenan containing samples than in low-fat samples without κ-carrageenan. It seems that the flow behaviour of κ-carrageenan containing samples is governed by the structure formed between the κ-carrageenan molecules and the casein micelles that can inhibit the microcrystal's aggregation. Probably in these systems inulin behaves only as a cosolute with the ability to bind water molecules. Paseephol et al. (2008) interpreted the effect of inulin addition on yogurt (decrease yield stress value and firmness) as an indication for the interference of inulin with the protein matrix formation due to the dispersion of inulin molecules among casein micelles. They suggested that this effect can be similar to the interference of fat globules on protein matrix formation. When inulin was incorporated into starch-based dairy desserts (Tárrega & Costell, 2006b; González-Tomás et al., 2008; González-Tomás, Bayarri, Coll-Marqués, et al., 2009a) different effects of inulin on samples with different starch concentration were observed, and these differences could be explained by the competition for water of inulin and starch. In the samples with lower starch concentrations (2.5 and 3.25%), there was sufficient water in the system and hence the addition of inulin did not influence the starch granule swelling process. For samples with the higher starch concentration (4%), with part of the water bound to the inulin chains, swelling of the starch granules was limited, the volume fraction of swollen particles was lower and the system viscosity decreased. Apart from the influence of inulin on rheological and mechanical properties of dairy products, González-Tomás, Bayarri, and Costell (2009b) showed that in starch-based dairy desserts a skimmed-milk dessert with 7.5% long-chain inulin and a whole-milk sample without inulin showed similar flow behaviour and were perceived having the same consistency although a certain roughness was also noted. The latter effect could be due to the presence of small crystals or crystal aggregates of long-chain inulin in the product. This was confirmed by Torres, Tárrega, and Costell (2010) in their study of the rheological properties and particle size distribution in dairy desserts containing long-chain inulin during storage. They

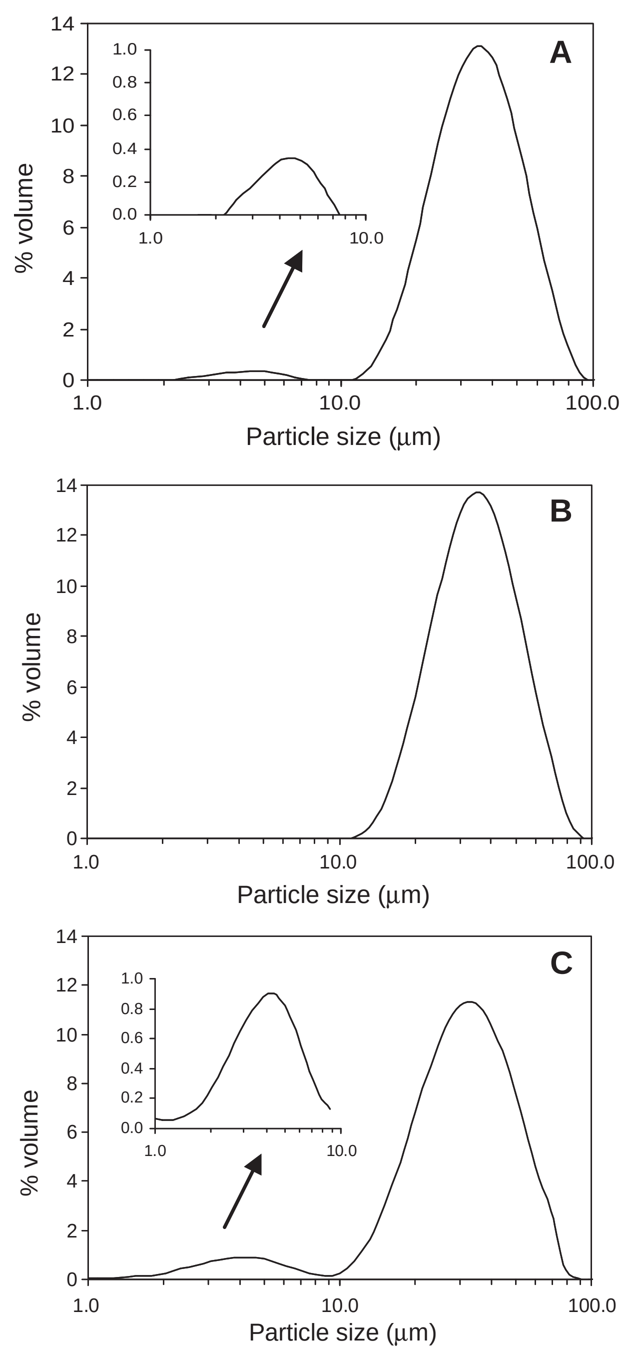

Fig. 2. Particle size distribution of starch based custard desserts made with whole-milk (A), with skimmed-milk (B) and with skimmed milk and 7.5% long chain inulin (C).

showed that control samples without inulin proved to be stable during storage but that the rheological properties of desserts containing inulin changed over time leading to a more thixotropic, consistent, pseudoplastic and elastic system. The changes occurred gradually over 6 days and seemed to settle on day seven. Samples containing inulin had particles smaller than 10 μm, in a size range similar to fat globules (Fig. 2). Aggregates were formed 2 days after preparation and the percentage of these increased during storage, following the same trend as the changes in rheological behaviour. Microstructural observations of starch-based dairy desserts formulated with whole-milk, skimmed-milk and skimmed-milk and long-chain inulin obtained with both Low Temperature Scanning Electron Microscopy and Light microscopy give more information about the characteristics of the inulin aggregates (Figs. 3 and 4). Cryo-SEM micrographs (Fig. 3) showed starch granules immersed in a continuous network mainly composed of milk proteins in all three samples. Fat globules were observed in the whole-milk sample (Fig. 3a). In the inulin sample (Fig. 3c) some aggregates formed embedded in this matrix. These aggregates were characterised by a rough outline with pointed edges. Light microscopy images showed that in whole-milk and skimmed-milk samples without inulin (Fig. 4a and b) particles are present that correspond to gelatinised starch granules. In the whole-milk samples fat globules were also observed in the continuous phase of the system. Skimmed-milk samples with inulin showed the presence of some large particles or aggregates and more very fine particles (Fig. 4c). This confirms that aggregation of inulin crystals took place in the continuous phase, thereby increasing the effective

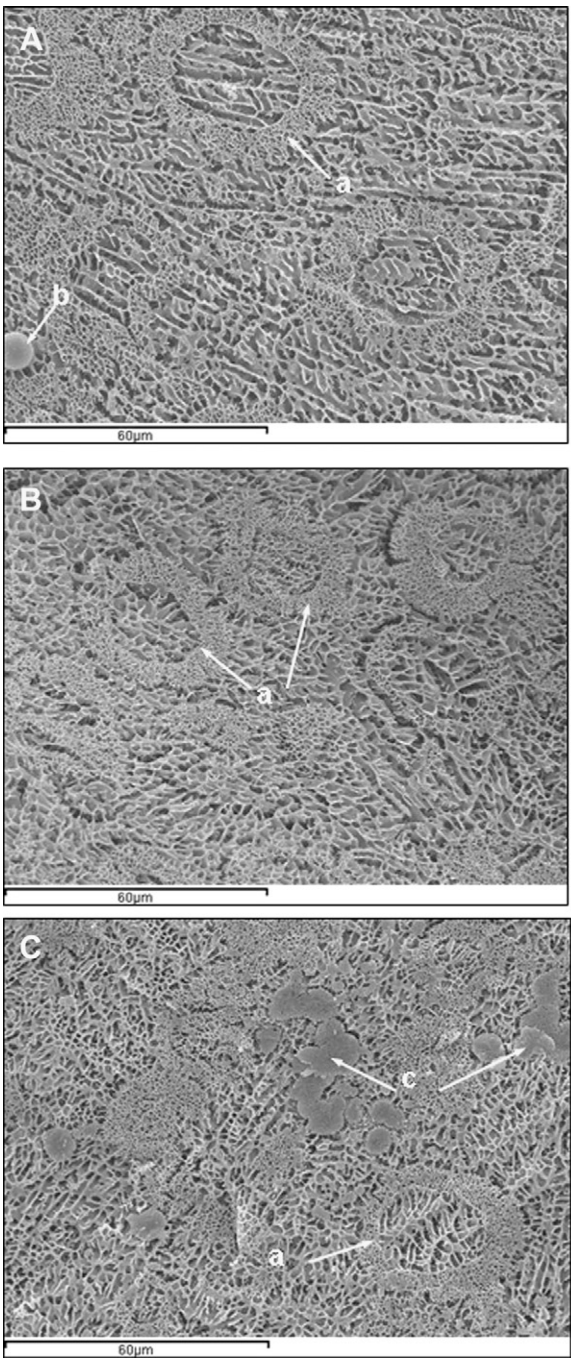

Fig. 3. Micrograph images (×1000) observed by Cryo-SEM of starch-based custard desserts formulated with whole-milk (A) skimmed-milk (B) and skimmed-milk with 7.5% long-chain inulin (C) showing starch granules (a), fat globules (b) and inulin aggregates (c).

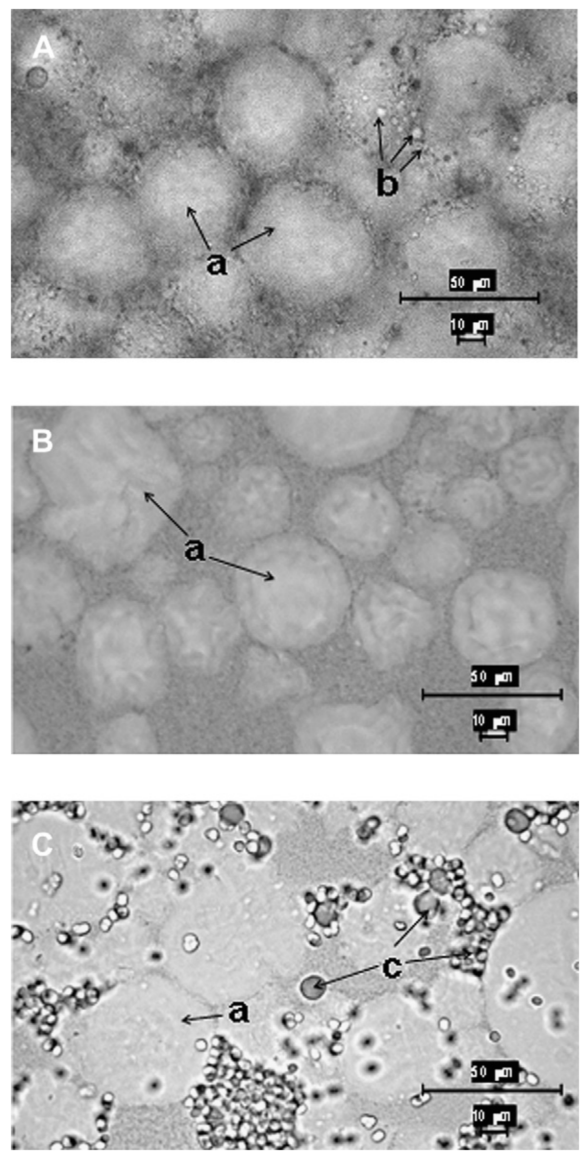

Fig. 4. Light micrograph images (×20) of starch-based custard desserts formulated with whole-milk (A), with skimmed-milk (B) and with skimmed-milk and 7.5% long-chain inulin (C) showing starch granules (a), fat globules (b) and inulin aggregates (c).

fraction volume, which could explain the important rheological and sensory changes observed in low-fat starch-based dairy desserts with long-chain inulin.

4. General conclusions

From the data presented above we can conclude that the effect of inulin on rheological behaviour and on texture in different dairy products clearly and not surprisingly not only depends on the concentration but also on the degree of polymerisation of the inulin. The inclusion of (long-chain) inulin in a dairy product as fat replacer can have different effects on the rheological properties and on texture depending on the structure and composition of each product. The effect is strongly influenced by the composition and structure of each dairy matrix, by fat content, by the type and concentration of other carbohydrates present in the product and by the inulin interactions with these other ingredients. The product structure and the presence of other ingredients especially hydrocolloids, can modify the rate and the extent of inulin crystallisation and thus influence its functionality as fat replacer. In some cases product rheology is determined largely by other components (such as in systems with starch or κ-carrageenan) with only minor effects of inulin, whereas at certain concentrations of long-chain inulin, this ingredient plays a more predominant role. It appears that the competition for moisture is a determining factor as they may determine whether starch can gelatinise completely or inulin can dissolve completely or form microcrystals or aggregates. Measuring bulk rheology may not always be sufficient as the relationship between bulk rheological parameters and creamy mouthfeel is not always clear; additional measurements for friction parameters could give additional information. This type of information can also be useful to gain a better understanding of the effect of inulin on oral processing and breakdown of the structure of dairy products (Foegeding et al., 2010).

At the same time it is also clear that for proper fat replacement not only the structure and its subsequent texture should be optimal, but also that flavour release should be taken into account (see De Wijk, Rasing, & Wilkinson, 2003). This aspect has not yet received much attention.

Inulin can act as a good fat replacer in different dairy products. The ability of inulin as fat replacer is not only related to the modification of rheological behaviour or the thickness or hardness of the product but also to changes of other mouthfeel attributes as creaminess or smoothness. It seems that, in general, to obtain low-fat products with rheology and thickness close to those of full-fat products, higher concentrations of inulin are needed than those necessary to mimic the creaminess or smoothness. Understanding the underlying mechanisms inducing the behaviour of inulin as fat replacer is important to design and develop low-fat inulin-enriched products with good sensory quality.

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