

Enrichment of yoghurt with oat protein fractions: Structure formation, textural properties and sensory evaluation



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ABSTRACT

Despite its excellent nutritional properties, unlike other cereals oat displays poor baking properties and therefore is mainly processed in products like rolled oats or serves as raw material for the functional ingredient β -glucan. During β -glucan production, a protein-rich fraction remains as a by-product. Functionalisation of this protein-rich oat-fraction and its application as a valuable food ingredient would improve the sustainability of the process. In the present study, oat protein-enriched cow's milk yoghurt was produced. The main foci were on the characterisation of techno-functional properties, as well as on the analysis of the organoleptic perception and sensory properties by a trained panel. Cow's milk yoghurt, following a traditional formulation with addition of skim milk powder (SMP), served as a reference. Oat protein was incorporated using two preparations: oat protein concentrate (OPC) and oat protein isolate (OPI). Fermentation of yoghurt enriched with SMP, OPC or OPI was monitored via pH-value, formation of lactic acid and rheological measurements. In addition, texture analysis and measurement of syneresis were performed and sensory properties were evaluated. Yoghurt containing SMP showed the highest strength in texture analysis but also a high rate of syneresis. Addition of OPC resulted in a product, which combines nutritional benefits with the sustainable use of the by-product of oat processing as well as improved product quality with respect to syneresis and sensory evaluation, especially mouthfeel. In case of OPI, strong sedimentation took place and high syneresis was observed. It is assumed that the compatibility of oat protein with milk proteins is low, which may be compensated by gelatinisation of starch during yoghurt production.

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1. Introduction

Yoghurt is one of the most popular food products and is consumed world-wide. Yoghurt gels are formed by fermentation of milk using lactic acid bacteria, most commonly used *Streptococcus thermophilus* and *Lactobacillus delbrückii* subsp. *Bulgaricus* (Lee & Lucey, 2010). The consumers' acceptance depends on sensory properties of the products such as texture, characteristic smell and taste (Jaworska, Waszkiewicz-Robak, Kolanowski, & Swiderski, 2005). While smell and taste can be modified or adapted subsequently, for example by adding fruit preparations, the texture of yoghurt can only be influenced by the production process. From the consumers' perspective, mouthfeel and creaminess are the essential properties of yoghurt (Guinard & Mazzucchelli, 1996; Lucey, 2004) whereas the typical yoghurt textural defects, low gel

strength and syneresis, negatively affect consumers' acceptance (Lee & Lucey, 2010; Lucey, 2004; Walstra, Wouters, & Geurts, 2005).

Enrichment with solids, which means in general the increase in non-fat milk solids, is traditionally achieved by the addition of skim milk powder (SMP), which was recently reviewed by Karam, Gaiani, Hosri, Burgain, and Scher (2013). An addition of 3–4% SMP is recommended (Tamime & Robinson, 2007). Enrichment with more than 6% SMP results in negative sensory impressions (Tamime & Robinson, 2007). Increasing the dry matter reduces typical problems like syneresis and low gel strength (Guzman-Gonzalez, Morais, Ramos, & Amigo, 1999; Karam et al., 2013). A yoghurt's texture can also be maintained and improved by utilisation of stabilisers such as modified starch, gelatine and pectin. However, the first group of different types of modified starch is often considered as unnatural and the acceptance by the consumers is low (Lucey, 2004). The yoghurt industry faces the challenge of achieving an economic production of yoghurt that not only meets the consumers' expectations regarding texture and taste, but also

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meets the growing demand for clean label products where food additives are concerned. This is where oat protein concentrate (OPC), obtained as an underutilised processing side stream from conventional β -glucan production, might provide an alternative to SMP and conventional thickeners. As a sustainable ingredient, OPC is not only a good source of health promoting valuable components such as dietary fibre, protein and bioactive compounds, but might also act as a functional ingredient in semi-solid foods like acid-induced gels due to its high protein and starch content.

Oat grains (*Avena sativa* L.) are generally highly accepted by consumers and a wide range of oat containing products like beverages, cereals and baked goods are consumed. Compared to other cereals oats have a high protein content as well as a more favourable composition of essential amino acids and, thus, a high nutritional value. However, oat – like all other cereals – lacks in lysine, the content is lower than the FAO amino acid scoring pattern requirements (Mäkinen, Sozer, Ercili-Cura, & Poutanen, 2017; Pedó, Sgarbieri, & Gutkoski, 1999; Sterna, Zute, & Brunava, 2016). In contrast, milk proteins provide a good source for this essential amino acid (Peterson, 2011). Therefore, a combination of cow milk and oat protein is favourable and increases the nutritional value of the resulting product.

The aim of the present study is to evaluate the impact of replacing skim milk powder by oat protein concentrate (by-product of cereal processing) on structure formation, textural properties as well as organoleptic perception and sensory properties. Oat protein concentrate, which was obtained after milling and air-classification of supercritical CO₂ defatted oat grits, contained approximately 43% protein, 33% starch and 3.4% ash. The oat protein isolate, which was produced from oat protein concentrate by alkaline extraction and isoelectric precipitation, contained approximately 90% oat protein and less than 1% starch. A yoghurt enriched with oat protein concentrate (1.1, 1.7 and 2.5% oat protein) and a yoghurt preparation with oat protein isolate were prepared and the product properties were compared to a classic yoghurt preparation with skim milk powder (SMP) as a reference. Thus, it was possible to analyse the role of starch and protein regarding the fermentation process as well as to the functional and sensory properties of the resulting oat protein enriched yoghurt.

2. Materials and methods

Oat protein concentrate (OPC) was obtained from supercritical CO₂ extracted, milled and air classified oat grits as described in the patent of Kaukovirta-Norja, Myllymäki, Aro, Hietaniemi, and Pihlava (2008). The oat protein isolate (OPI) was produced from OPC by alkaline extraction according to the method of Liu et al. (2009) with slight modifications. The extraction was performed at pH 9.2, followed by isoelectric precipitation at pH 5, washing with distilled water, pH adjustment to pH 7 and subsequent freeze-drying. Lactose was obtained from Sigma-Aldrich Chemie GmbH, Munich, Germany. Skim milk powder (SMP) was purchased from frema Reform von Heirler Cenovis GmbH (Radolfzell, Germany). Fresh, pasteurised milk with a fat-content of 1.5% was purchased at a local supermarket.

2.1. Protein solubility

OPC and OPI were suspended at a concentration of 5% (w/w) in distilled water by magnetic stirring at room temperature for 1 h. The pH was adjusted as required to pH 4 or 7 with 1 N NaOH or 1 N HCl. The suspension was centrifuged at 10.000 g for 10 min (Sigma 3K12, Sigma Laborzentrifugen GmbH, Osterode am Harz, Germany) and the protein content in the supernatant as well as in the suspension before centrifugation was determined according to Dumas

method (Dumatherm N64+, Gerhardt, Königswinter, Germany). A factor of 6.25 was used to convert nitrogen to crude protein content. The relation of the protein content in the suspension to the protein content in the suspension before centrifugation is the protein solubility [%].

2.2. Yoghurt preparation and fermentation

OPC, OPI/lactose and SMP were suspended in 500 g milk. Three levels of enrichment resulting in 12.3, 13.8 and 15.3% dry matter were evaluated, for exact amounts please refer to Table 1. Due to the poor solubility of the OPI, the corresponding samples were pre-treated using a single pass in a homogenizer Panda Plus model (Niro Soavi, Germany) at 200 bar. All samples were stirred for 30 min at 37 °C in the Thermomix TM31 (Vorwerk, Wuppertal, Germany). Subsequently, the temperature was adjusted to 80 °C and held for 20 min. Water loss was determined and dry matter was adjusted to the desired level. The mixture was then cooled to 40 °C in a water bath and 0.2 U yoghurt culture containing *Lactobacillus delbrückii* subsp. *Bulgaricus* and *Streptococcus thermophilus* (YC-X11 Yo-Flex, Chr. Hansen, Denmark) were added. The mixture was stirred for 15 min. Finally, the samples were fermented in a water bath at 40 °C for 24 h. The yoghurt was stored at 6 °C until analysis.

2.3. Determination of lactic acid and pH

L-lactic acid concentration of the fermented samples after 3 and 24 h was determined by a colorimetric assay for the determination of lactic acid in foodstuffs and other materials according to the instruction manual (R-biopharm AG, Darmstadt, Germany). The pH-value was measured every hour during fermentation (pH-meter Lab 865 and BlueLine 18 pH-electrode, SI Analytics GmbH, Mainz, Germany).

2.4. Rheological measurements

Oscillatory measurements were performed using a rheometer (UDS 200, Anton Paar GmbH, Ostfildern, Germany) equipped with a concentric measuring cylinder (Z3 DIN). Fermentation was monitored up to 16 h at 40 °C in time sweep mode (deformation: $\gamma = 10^{-3}$, frequency: 1 Hz) followed by a cooling step to 10 °C within 30 min and subsequently a frequency sweep (deformation: $\gamma = 10^{-3}$, frequency: 0.01–10 Hz) and amplitude sweep (deformation: $\gamma = 10^{-3}$ to 10, frequency: 1 Hz). All measurements were performed in duplicate.

2.5. Texture analysis – determination of gel strength

The texture of the yoghurt samples was evaluated by a penetration test after storage for 24 h at 6 °C. A force-path diagram was

Table 1
Dosages of ingredients used for the production of yoghurt samples.

| Dry matter [%] | Dosage [%] |
|----------------|---------------------|
| 12.3 | 2.5 OPC |
| | 2.4 SMP |
| | 1.2 OPI/1.2 Lactose |
| 13.8 | 4.4 OPC |
| | 4.1 SMP |
| | 1.7 OPI/2.4 Lactose |
| 15.3 | 6.2 OPC |
| | 5.9 SMP |
| | 2.2 OPI/3.5 Lactose |

obtained. The gel strength is the maximum force required to penetrate into the sample at a given speed and a fixed distance. The penetration test was carried out with the material testing machine Z0.5 Basic Line (Zwick GmbH & Co KG, Ulm, Germany) and 100 N-load cell (KAD-Z, A.S.T. GmbH Dresden, Dresden, Germany) using a cylinder (diameter: 12 mm). The speed was 2 mm/s and the penetration depth 20 mm.

2.6. Water holding capacity

The water holding capacity of the yoghurt samples was determined by the method of [Guzman-Gonzalez et al. \(1999\)](#). For this purpose, after storage of the yoghurt for 24 h at 6 °C, 25 g sample were weighed into a glass and centrifuged (Sigma 6K10, Sigma Laborzentrifugen GmbH, Osterode, Germany) at 500 g for 10 min at room temperature. The supernatant was then removed by means of a pipette and weighed. The water holding capacity was determined in triplicate and is calculated as follows:

$$WHC = \left(1 - \frac{m_s}{m_y}\right) \cdot 100\%$$

WHC is the water holding capacity of the sample, m_s the supernatant after centrifugation and m_y the mass of the weighed yoghurt.

2.7. Sensory analysis

For the sensory evaluation, yoghurt samples enriched with OPC and SMP at low (12.3%) and medium (13.8%) dry matter were chosen because they had the best physical properties. The yoghurt with OPI was not included, because rheological and texture measurements had already revealed insufficient product properties.

Eleven trained panellists evaluated the sensory attributes of yoghurt. A profile test with twelve predefined characteristic properties such as colour, loss of whey, yoghurt flavour, lactic fermented flavour, sweetness, sourness, bitterness, oat flavour, off-flavour, mouthfeel, creaminess and sliminess was applied. A scaling of the intensity between 0 and 5 with 0.5 steps was chosen with 0 being the weakest and 5 the strongest feature expression. The mouthfeel was evaluated from 0 = smooth to 5 = strongly particulate. The samples were equilibrated to room temperature after storage for 24 h at 6 °C and a heaped teaspoon per person and sample was prepared on a small dish 30 min before the sensory test.

2.8. Statistics

The Design expert 8 program (Stat Ease Inc., Minneapolis, USA) was applied to analyse the influence of 'dry matter' (12.3, 13.8 and 15.3%) and 'type of supplement' (SMP, OPC and OPI) on physical properties of the yoghurt (G'_{16h} , G''_{16h} , WHC and gel firmness). A general factorial design was chosen. Furthermore, the one-factor ANOVA and the Scheffé test were carried out with the program GNU PSPP 0.10.2 (GNU Operating System, Free Software Foundation, Inc.) to evaluate the results of the sensory profile analysis.

3. Results and discussion

3.1. Effect of oat protein enrichment on structure formation

During fermentation of milk with lactic acid bacteria, lactose is converted into lactic acid, which leads to an acidification of the product. Several physicochemical changes of the casein micelles occur, resulting in the conversion of the fluid milk into a viscoelastic gel. The storage modulus G' - representing elastic properties - and

the loss modulus G'' - representing viscous properties - are determined by rheological measurements. The formation of the three-dimensional network results in a steep increase in the storage modulus G' ([Haque, Richardson, & Morris, 2001](#)). The pH profile and the storage modulus of the yoghurts containing SMP, OPI/lactose or OPC at three contents of dry matter are shown in [Fig. 1](#).

The fermentation process can typically be divided into three phases:

- 1) lag phase with adaptation of the microorganism to the medium, characterised by slow pH decrease and no change in G' ,
- 2) logarithmic phase with a rapid pH decrease and rapid increase in G' and
- 3) decelerated acidification with a slowdown in G' ([Soukoulis, Panagiotidis, Koureli, & Tzia, 2007](#)).

All three phases can be observed in [Fig. 1](#). The experimental results show a faster onset of gel formation (shorter lag phase) for OPC and OPI enriched samples compared to SMP enriched yoghurt (G' increases earlier in [Fig. 1](#)). In case of OPC enriched samples, the early onset of gel formation can be explained by the fast acidification (faster pH reduction). The gel formation in acidified milk gels comprises the reduction of the net negative charge on casein and the increase in the rate of solubilised colloidal calcium phosphate which will decrease the electrostatic repulsion as well as the steric stabilisation and will increase casein–casein interactions leading to the formation of a three-dimensional acid milk gel ([Lee & Lucey, 2010](#)). According to [Lucey \(2004\)](#), gel formation of yoghurt starts at a pH of 5.3. A linear interpolation of the pH-values in [Fig. 1](#) shows that gel formation starts at pH 5.8 for OPC enriched yoghurt after 2 h and at pH 5.6 for SMP enriched yoghurts after 3 h and 20 min. Considering the discontinuous recording of the pH-value and the linear interpolation, the slight deviation is negligible and the discrepancy between the measured and the expected values can be explained this way.

Though at the beginning of the fermentation the same amount of lactic acid bacteria was added to all samples, acidification (reduction of pH) was faster for the OPC enriched samples ([Fig. 1](#)) in comparison to all other samples. The variation in the rate of acidification can be attributed either to a different activity of the lactic acid bacteria or to the different buffering capacity of the additives OPC, OPI and SMP. However, the measurement of the lactic acid content at the time of maximum pH difference, 3 h after the start of fermentation ([Table 2](#)), showed that there was no significant difference between OPC, SMP and OPI enriched yoghurt. These data indicate that the activity of the lactic acid bacteria was similar in all samples. From literature it is known, that SMP has a high buffering capacity ([Peng, Serra, Horne, & Lucey, 2009](#); [Salaün, Mietton, & Gaucheron, 2005](#); [Zare, Boye, Orsat, Champagne, & Simpson, 2011](#)). With this background, the faster acidification of the OPC samples must be attributed to a lower buffering capacity of this protein.

Interestingly, acidification (graph of the pH in [Fig. 1](#)) of OPI enriched samples is similar to SMP, though OPI is an extract of OPC. This high buffering capacity of OPI could be traced back to the recovery process by isoelectric precipitation (dissolution of the protein in the alkaline medium by addition of sodium hydroxide solution, followed by precipitation by means of HCl in the acidic environment). Nevertheless, the storage modulus of OPI increased faster than that of SMP and the gel formation started already at pH 6.3 after 2 h and 20 min.

In the OPI containing sample sedimentation was observed during sample production and was reflected by a decrease of G' over time for OPI ([Fig. 1](#)). Considering the poor solubility of oat protein between pH 4 and 7 as reported by [Loponen, Laine, Sontag-](#)

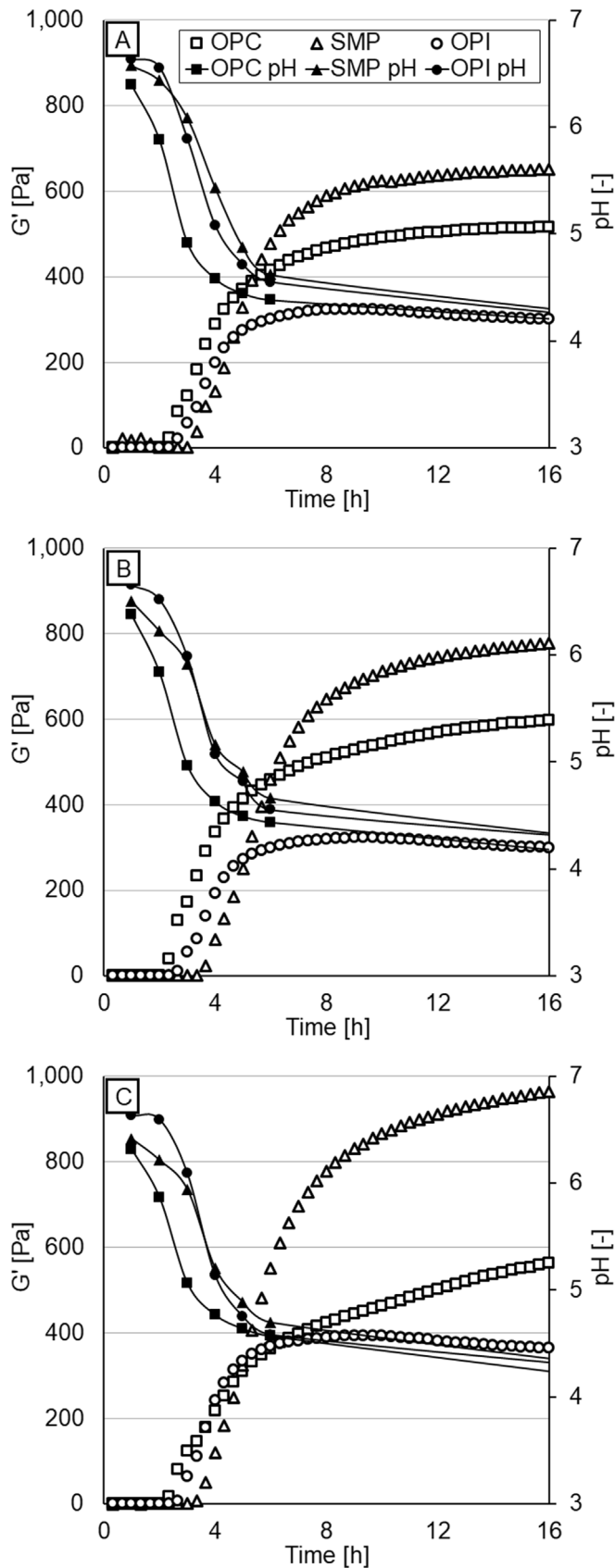


Fig. 1. Storage modulus G' (empty indicators – left y-axis) and pH (filled indicator – right y-axis) trends during fermentation of milk enriched with OPC, OPI/lactose or SMP at 12.3 (A), 13.8 (B) and 15.3% (C) of dry matter.

Table 2
Development of lactic acid content [g/100 g] after 3 and 24 h.

| Dry matter [%] | Material | Fermentation time | |
|----------------|----------|-------------------|-----------------|
| | | 3 h | 24 h |
| 12.3 | OPC | 0.26 ± 0.02 | 0.39 ± 0.06 |
| | SMP | 0.21 ± 0.04 | 0.34 ± 0.02 |
| | OPI | 0.31 ± 0.02 | 0.38 ± 0.1 |
| 13.8 | OPC | 0.30 ± 0.01 | 0.38 ± 0.05 |
| | SMP | 0.28 ± 0.08 | 0.43 ± 0.08 |
| | OPI | 0.27 ± 0.01 | 0.39 ± 0.08 |
| 15.3 | OPC | 0.25 ± 0.03 | 0.43 ± 0.05 |
| | SMP | 0.28 ± 0.08 | 0.59 ± 0.04 |
| | OPI | 0.28 ± 0.01 | 0.44 ± 0.03 |

Strohm, and Salovaara (2007), the following hypothesis can be stated: Owing to the poor solubility of the oat protein, large aggregates like solid structures or particles are formed and increase the elastic components in the system. During acidification, these larger clusters are poorly incorporated into the casein network of the yoghurt due to an incompatibility between milk and oat proteins and the resulting gel is less elastic (lower value of G' of OPI in Fig. 1).

Generally, three factors affect the compatibility of proteins: (1) different solubility in the solvent (2) different molecular weight and (3) differences in the conformation (Polyakov, Grinberg, & Tolstoguzov, 1997). Protein solubility of both OPC and OPI is pH dependent (Fig. 2). At pH 7, which is close to the pH of milk, solubility of OPC and OPI was found to be around 30%, Fig. 2. The solubility was reduced by acidification (reduction to pH 4) to below 15% for OPI and OPC, indicating aggregation, segregation and sedimentation processes. Similar results for the pH-dependence of the solubility of oat proteins have also been reported by Loponen et al. (2007) and Konak et al. (2014). Caseins in milk are associated in the form of micelles. Due to interaction of the hydrophilic ends of the κ -casein, located on the surface of the micelle, with the aqueous solvent, a good solubility is maintained (Fox & Brodtkorb, 2008). Thus, casein micelles are solubilised in milk. According to Polyakov et al. (1997), a difference in solubility is the main factor for the incompatibility of proteins. Casein micelles have a size of 50–500 nm with an average of 120 nm. Each micelle is reported to have a molecular mass of $1.3 \cdot 10^6$ kDa in hydrated form (Fox & Brodtkorb, 2008). The oat globulins are smaller with approximately 320 kDa in their hexameric form (Peterson, 1978). Polyakov et al. (1997) determined phase diagrams for some protein 1 – protein 2 – water systems. They are asymmetrical and the binodal curve (curve under which the proteins are compatible) is always located closer to the concentration axis of the protein of lower molecular weight. For the oat globulins and caseins this means that, as the oat globulin concentration increases, the compatibility range under the binodal curve decreases disproportionately, allowing only the addition of a small amount of oat globulins until phase separation will occur.

Conformation of the proteins describes, whether they are native or unfolded (Polyakov et al., 1997). Since the heating of the yoghurt preparations took place at 80 °C, due to the heat stability no conformational changes are likely to occur, neither of oat globulin nor casein (Mäkinen et al., 2017; Singh, 2004). Nevertheless, casein-whey protein complexes will be formed in the course of heating (recently reviewed in Donato and Guyomarc'h (2009)), which will increase the size and the molecular weight of the casein micelles and will reduce the compatibility according to factor (2).

Due to the varying solubility, the different molecular weight and differences in conformation in the present case oat and milk

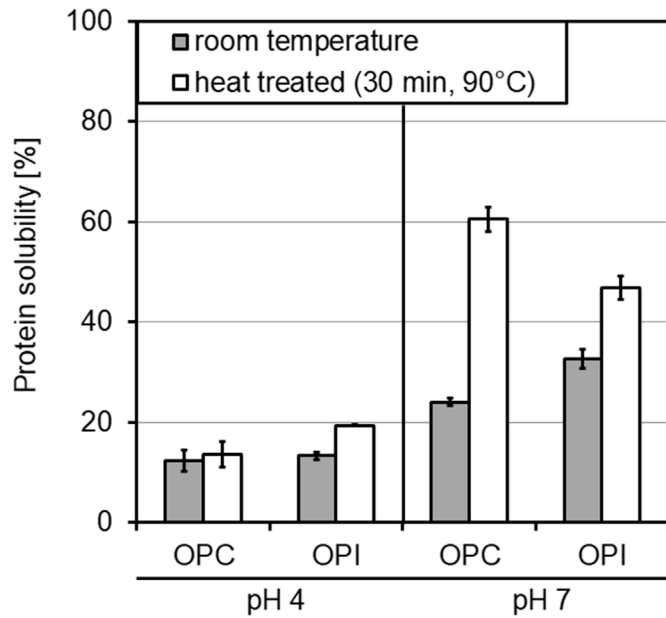


Fig. 2. Protein solubility [%] of OPC and OPI suspensions at pH 4 or 7.

proteins are probably more or less incompatible. Thus, a structure weakening effect can be observed and sedimentation is conceivable (indicated also by the decreasing G' over time for OPI in Fig. 1). In case of OPC enrichment, the starch fraction (0.8, 1.5 and 2%) can mask the milk-oat-protein-incompatibility. There might be two processes being involved in the covering of the incompatibility: 1. during heat-treatment of the yoghurt premix, the starch gelatinises, binds water (Considine et al., 2011) and the viscosity is increased. 2. On the other hand, binding of water by gelatinised starch reduces the available quantity of free water in the whole system. Thus, a concentration effect of the milk proteins in the remaining water phase takes place. Consequently, a denser packaging of milk proteins will occur leading to increased elasticity.

3.2. Influence of oat protein on product properties

After 24 h of fermentation, all samples had a pH value of approximately 4. This is below the typical yoghurt pH of 4.6 (Lee & Lucey, 2010), but can be explained by the duration of the fermentation. In case of industrially produced yoghurt, the product would be cooled immediately after reaching the desired pH in order to stop further acidification.

Statistical analysis shows a significant effect of dry matter, type of supplement and interactions of both factors on the resulting structural parameters G' and G'' after 16 h fermentation time (see interaction graphs in Fig. 3 and ANOVA Tables 1 and 2 in Suppl. Material). In addition, significant influence of dry matter and type of supplement on the gel strength were found (ANOVA Table 3 in the Suppl. Material). The samples containing oat protein possessed a significantly lower gel strength compared to SMP enriched yoghurt (Fig. 4). This can be explained by the lower elasticity of the OPC and OPI samples, i.e. a less solid-like behaviour (Fig. 1). This connection between gel strength and elasticity (storage modulus) was also described by Paseephol, Small, and Sherkat (2008).

While dry matter has a strong effect on G'_{16h} , G''_{16h} and gel strength of yoghurt enriched with SMP, only little effect was observed for OPC and OPI enriched samples. In native milk, casein micelles possess a high net negative charge, which is reduced as the

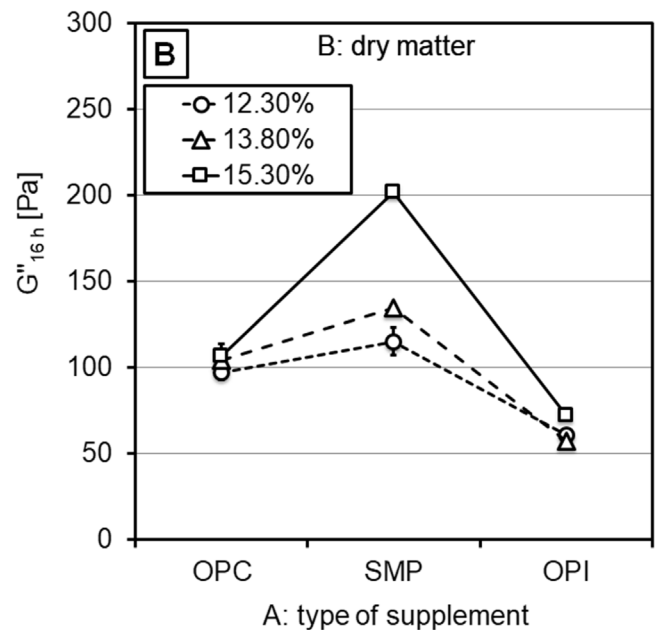
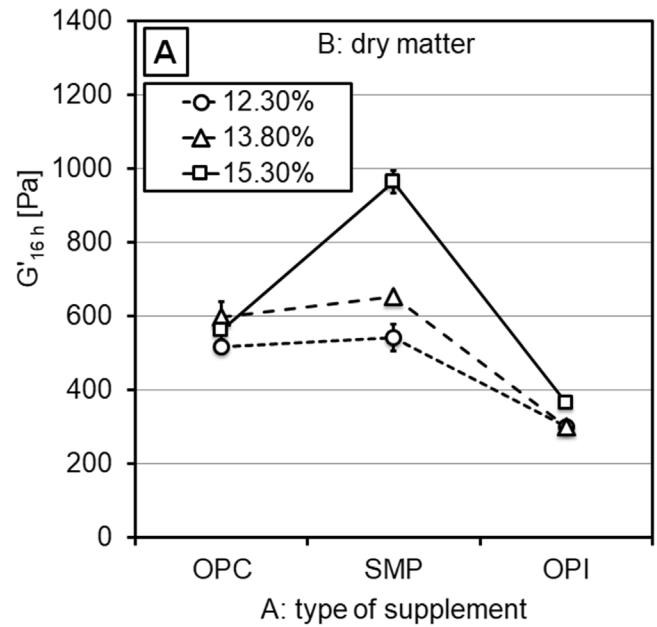


Fig. 3. Interactiongraphs (Design-Expert®) of factors G'_{16h} (A) and G''_{16h} (B). Variables are type of supplement (OPC, SMP and OPI) and dry matter (DM) (12.3, 13.8 and 15.3%).

pH decreases. As an effect of reduction in surface charge, casein micelles approach and aggregate. These aggregates are connected through hydrophobic and electrostatic interactions (Lucey, 2004). At the isoelectric point of denatured β -lactoglobulin around pH 5.3 (Lucey, 2004) the net charge of the denatured β -lactoglobulin is minimal. Consequently, β -lactoglobulin- κ -casein complexes, which were formed during the preheating of the milk, lead to an aggregation of the casein micelle via β -lactoglobulin bridges. A further pH reduction destabilises the casein micelles by the dissolution of the colloidal calcium phosphate (Lee & Lucey, 2010). Near the isoelectric point of the caseins (pH 4.6), the casein molecules aggregate through hydrophobic and electrostatic interactions (Lucey, 2004) and the three-dimensional network is formed. For SMP, a fortifier which already contains casein, an increase in dry matter

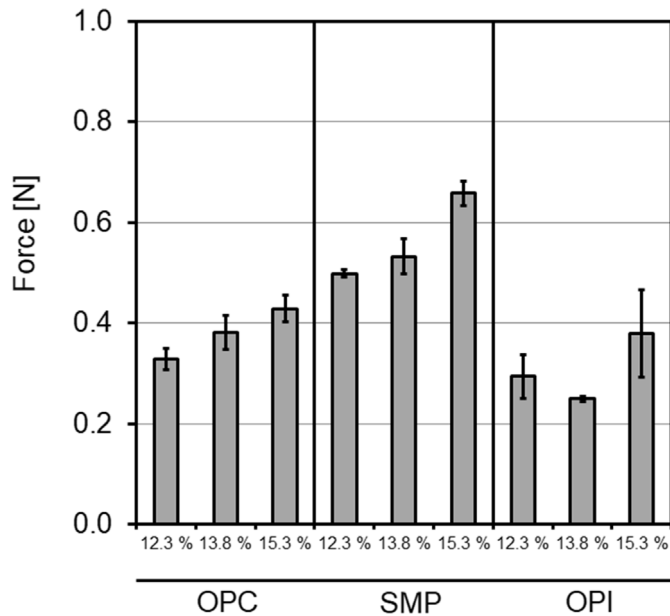


Fig. 4. Gel strength obtained by texture analysis of yoghurt made of milk enriched with OPC, SMP or OPI/lactose.

will result in an increased amount of casein. As a consequence, more binding sites will be present, the pores (filled with whey) will become smaller within the three dimensional network and the matrix will become more dense (Harwalkar & Kalab, 1986). Thus, a network with strong elastic properties as well as high gel strength will be obtained. This relationship between increasing dry matter and increase in gel strength was also described by Harwalkar and Kalab (1986) and Amatayakul, Sherkat, and Shah (2006). The lack of pronounced effects when adding OPI or OPC leads to the presumption, that no interaction takes place between casein micelles and oat protein. Consequently, an increase in dry matter was found to have only little effect on the elastic properties of the gel (Fig. 3).

The gel strength of the OPI enriched yoghurt is influenced by the strong sedimentation. Thus, strong variations are observed, Fig. 4. Presumably, no interaction takes place between casein micelles and oat protein.

The water holding capacity gives information about the stability of the gel samples and, thus, about their tendency to syneresis. Statistical analysis proved a significant influence of dry matter and type of supplement on water holding capacity (ANOVA Table 4 in Suppl. Material). The yoghurt samples containing OPC revealed a higher water holding capacity compared to those with SMP and samples containing OPI had the lowest water-holding capacity (Fig. 5). It is concluded that not the oat protein, but the oat starch in the OPC improved the water holding capacity of the yoghurt samples and reduced syneresis. Ares et al. (2007) added starch and gelatine to yoghurt and found a significant effect on the syneresis. While gelatine prevented syneresis completely, the addition of 5 mg starch/g only reduced it. In the present study, with the 12.3% dry matter in case of OPC 8 mg starch/g yoghurt were added. The starch fraction swelled and bound water during gelatinisation in the heating step (Considine et al., 2011).

In contrast, OPI and SMP contain no starch. If only OPI and SMP samples are compared, the significantly lower water holding capacity of OPI enriched yoghurt can be explained by a weaker and more unstable network of OPI enriched yoghurt because of fewer and weaker bonds in this network. This was also supported by the rheological results (lower G' in Fig. 1). OPI had a significantly lower

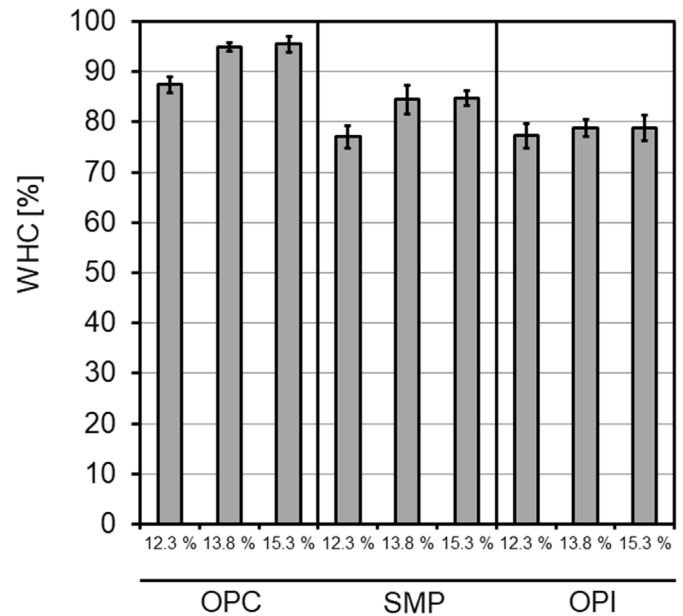


Fig. 5. Water holding capacity of yoghurt made of milk enriched with OPC, SMP or OPI/lactose.

storage modulus G'_{16h} than SMP and the storage modulus even decreased during fermentation, see Fig. 1.

3.3. Sensory profile analysis: influence of oat protein concentrate on the sensory product properties of the yoghurts

Results of sensory profile analysis are summarised in Fig. 6. The tendency for syneresis was significantly lower and creaminess was significantly improved for the OPC_{13.8%} sample compared to SMP_{12.3%}. However, a significant bitter taste from the oat was found ($p > 0.05$) (Table 5 in the Suppl. Material). An oat flavour was significantly perceived in all OPC enriched samples compared to the SMP enriched sample with 12.3% dry matter but not for the SMP enriched sample with higher amount of SMP ($p > 0.05$) (Table 5 in the Suppl. Material). Isleten and Karagul-Yuceer (2006) reported for yoghurts made from SMP a fermented, cereal-type flavour. As long as oat flavour is comparable to a cereal-type, this might explain why no significant difference in the oat flavour was found between yoghurts containing OPC and a high amount of SMP in the present

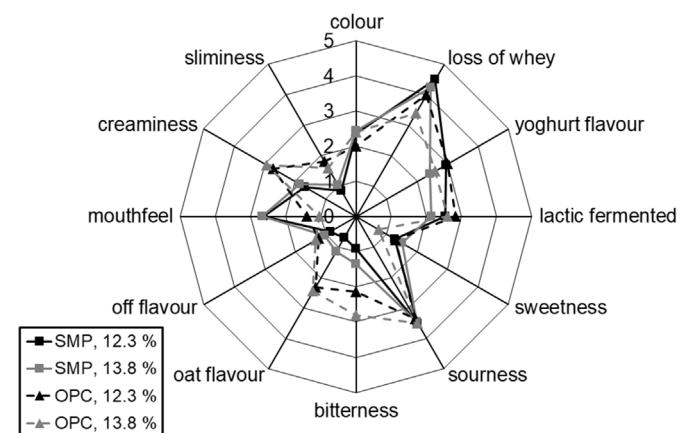


Fig. 6. Sensory profile of yoghurt enriched with SMP and OPC at 12.3 and 13.8% dry matter.

study. Karagül-Yüceer, Cadwallader, and Drake (2002) stated that the cereal flavour might be a result of compounds formed during heating of SMP such as furaneol, methional, 2-acetyl-1-pyrroline, thioazoline, and thiazole. Pyrroles and thiazoles have also been reported to be flavour compounds in extruded oat flours (Heydanek & McGorin, 1986; Parker, Hassell, Mottram, & Guy, 2000).

OPC enrichment had the highest impact on the mouthfeel. In this case, only the difference between SMP_{12.3%} and OPC_{12.3%} was not significant ($p > 0.05$) (Table 5 in the Suppl. Material). OPC enrichment resulted in an improved, smooth texture, with less particulation. An improved creaminess and mouthfeel after addition of starch and gelatine was also reported by Ares et al. (2007). The improvement of the texture by addition of starch might be due to its swelling and gelatinisation behaviour during the heating step and its ability to bind water and increase the viscosity (Williams, Glagovskaia, & Augustin, 2004). Even though OPC enrichment showed a significant increase in bitterness and oat flavour, this was not perceived as off flavour and the yoghurt flavour, sweetness, sourness and sliminess were also unaffected.

4. Conclusion

In the present study, yoghurt was enriched with two oat protein products, one concentrate (OPC) and one isolate (OPI). Structural parameters as well as sensory properties were evaluated and compared to conventional yoghurt enriched with skim milk powder (SMP). As could be seen in the fermentation experiments with OPI, the compatibility of highly purified isolated oat protein with milk proteins is low, and should therefore be considered more for its nutritional benefits, than for its techno-functionality. In contrast, OPC is found to be a good replacer of SMP because an improved product quality with respect to syneresis and mouthfeel is obtained. Since it is a by-product of cereal processing, the utilisation of OPC in other food products improves the sustainability of the process. In addition, OPC due to the excellent techno-functional properties of the contained oat starch is an appropriate ingredient for the implementation of nutritional valuable oat protein, giving a healthier and even more natural image to the yoghurt.

The production of yoghurt from oat protein in general and oat protein concentrate in particular has yet to be investigated more extensively as long as consumers expect healthy (probiotic) and also vegetarian or vegan products as well as products being free from genetically modified plant material. Thus, future work will focus on the development of vegan products to gain more knowledge on structure formation and physical properties of such products as well as to evaluate consumers' point of view, their impressions, liking and acceptability.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.foodhyd.2018.03.019>.

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