Recent advances in oat-based functional cereal products

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Abstract

This paper is a product of a doctoral thesis on developing oat-based functional products in correlation with consumer perception of health risks, funded by POSDRU project 107/1.5/S/76888. The analysis of the recent literature revealed a massive interest in oat-based functional products and that technological improvements were made to develop more such products. Oat proved to be a valuable ingredient that could improve considerably the nutritious value of cereal products like bread, pasta, noodles or cakes and, more specifically, gluten-free products. The main technological improvements investigated were the utilization of process optimization in terms of water and gluten addition, use of high hydrostatic pressure, enzyme treatment, sour dough addition, endogenous enzyme inactivation and, specifically for gluten-free products, replacement of α-gliadins with oat avenins. Recent studies also showed extrusion to be an advantageous method to produce oat-based products. New health benefits of oats with health claim potential were identified, like antioxidant capacity, reduction of atherogenesis, and hypoglycaemic and inhibitory effects on intestinal dissaccharidases. Moreover, the literature highlighted the importance of consumer acceptance and appeal in order to include oat-based functional food in their daily diets so to reach the necessary intake levels to get the currently claimed health effects.

Key words: functional food, oat, gluten-free, bread, β-glucan, dietary fibre enrichment

Introduction

Oat (Avena sativa) is an under-utilised grain in human nutrition, yet it is a good source of dietary fibre, especially β-glucan, essential amino-acids, unsaturated fatty acids, vitamins, minerals and antioxidants (E.K. HÜTTNER & E.K. ARENDT [1]). Oat bran in particular is a good source of B complex vitamins, protein, fat, minerals and β-glucan. The β-glucan has outstanding functional properties and is of immense importance in human nutrition. Different physiological effects of β-glucan are related to its viscosity, attenuation of post-prandial plasma glucose and insulin responses, high transport of bile acids towards lower parts of the intestinal tract and high excretion of bile acids thereby lowering of serum cholesterol levels (M.S. BUTT & al. [2]). Moreover, oat is also suitable for most coeliac patients and helps them enrich and diversify their diet, by having a higher nutritious value than conventional gluten-free ingredients (E.K. HÜTTNER & E.K. ARENDT [1]).

The European Food Safety Authority (EFSA [3], [4], [5]) has approved the following health claims for oats: ‘Regular consumption of β-glucans contributes to maintenance of normal blood cholesterol concentrations’; ‘Consumption of β-glucans from oats or barley contributes to the reduction of the glucose rise after a meal’; ‘Oat grain fibre contributes to an increase in faecal bulk’; ‘Oat β-glucan has been shown to lower/reduce blood cholesterol. Blood cholesterol lowering may reduce the risk of (coronary) heart disease’. Also, the Food and Drug Administration (FDA) recognized since 1997 the efficacy of oat β-glucan in
reducing the risk of coronary heart disease (E.K. HÜTTNER & E.K. ARENDT [1]). However, in order to obtain the cholesterol claimed effects, at least 3 g of β-glucans from oats per day or 0.75 g per portion should be consumed, while for the reduction of post-prandial glycaemic responses, the intake of 4 g of β-glucans for each 30 g of available carbohydrate per meal is needed according to FDA and EFSA recommendations.

Additional oat benefits that were recently researched on mice are the hypoglycaemic effects and inhibitory effect on intestinal disaccharidases of oat β-glucan (J. DONG & al. [6]), and the reduction of atherogenesis (K.E. ANDERSSON & al. [7]). In S. RAGAEE & al. [8], it is highlighted that the outer layer and germ of oat grain represent a rich source of bioactive components (e.g. dietary fibres, antioxidants, phenolics, lignin, vitamins, minerals) linked to the reduced risk of cardiovascular disease, cancer, diabetes, obesity and coronary heart disease. S. ZILIC & al. [9] observed a high content of lipid soluble antioxidants (tocopherols, yellow pigments) and phenolics (polyvinylpolypyrrolidone bound phenolics, ferulic acid) in hulless oat (*Avena nuda*), representing an important source for the development of functional foods. L. RYAN & al. [10] also found that consumption of oat-based breakfast cereals in general could be a significant contributor to the total polyphenol content and antioxidant potential of the diet.

This paper reviews recent refereed published literature particularly associated with the opportunities presented by oat as a functional ingredient in cereal products. By reviewing the available literature, possible approaches for the food industry and topics for further research are identified.

**Methodology for the review**

The search strategy for the present review sought recent published scientific work associated with oats’ potential as functional ingredient, with a focus on functional bread, in the English language. The search was conducted in September-October 2012, on the online database Science Direct, looking for references dating from 2010 onwards, using the terms “oat functional ingredient”.

A further search was conducted of the terms “oat functional bread”, dating from 2008, in order to further narrow the subject of the present review.

After reading the abstracts of the 61 papers gathered, in order to determine which paper was relevant, a total of 30 papers were read in full and referenced in the review. Out of the total number of refereed articles, four were reviews (M.S. BUTT & al. [2], A. K TENIOUDAKI & E. GALLAGHER [11], E.K. HÜTTNER & E.K. ARENDT [1], F. ROBIN & al. [12]).

Any search result that was unrelated to oat-based functional cereal products was excluded, mainly articles on functional beverages enriched with β-glucans and articles on β-glucan extraction process.

Limiting the search to refereed papers ensures that conclusions are drawn only from credible, high quality material that has undergone a process of unbiased evaluation involving qualified third party experts within the field.

**Current status of oat as functional ingredient in mixed cereal products**

Oat, among other cereals, is often used to enrich baked and extruded cereal products with fibre. In their review, A. KTENIOUDAKI & E. GALLAGHER [11] highlighted that levels of dietary fibre in oats have been reported to be between 10.6% in naked varieties and 18.5-23.4% in hulled varieties, while β-glucan component ranged between 4.5 and 5.6%. The total dietary fibre of oat bran was found to vary between 20.4 and 26.4%.
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Technological progress is needed to allow higher amounts of oats to be incorporated in cereal products to deliver the expected health benefits and, in the same time, to be accepted by consumers. This is emphasized in a study by U. TIWARI & E. CUMMINS [13], where a β-glucan human exposure assessment model was developed for an oat bread, to compare the resulting exposure to the current FDA recommendation. The model highlights that only at the highest substitution rate of 70% oat – 30% wheat flour, the FDA recommended intake for a health claim would be met when consuming the oat based bread.

In a study by S. RAGAEE & al. [8], whole oat flour was added to white flour at a replacement level of 30 g/100 g, to observe the effects of fibres on phenolic compounds, antioxidant capacity, dietary fibre fractions, and starch digestibility in vitro. This incorporation level increased free and bound phenolics and antioxidant capacity, demonstrating the potential of this grain to boost antioxidant properties of cereal products, such bread. Soluble, insoluble and total dietary fibre fractions and total minerals also increased. On the other hand, rapidly and slowly digestible and resistant starches were not significantly influenced by this addition.

Nevertheless, the fibre enrichment process poses some technological problems, as fibre has a weakening effect on dough and optimum dough development requires an increase in the quantity of water and mixing time. Oat fibre supplemented dough presents a lower extensibility, indicating a stiffer dough of higher consistency and lower tendency to flow. Breads made with oat flour improved in terms of volume and texture by optimizing the amount of water and gluten added. Longer proofing time at a high temperature (39-40°C) gave the highest loaf volume with the softer crumb texture (A. KTENIOUDAKI & E. GALLAGHER [11]).

Farinograph and extensograph tests were applied to determine the effect of oat wholemeal and carob fibre on the rheological properties of wheat flour dough (A. MIS & al. [14]). The applied additions of oat wholemeal (5-25%) and carob fibre (1-5%) increased the water absorption of the dough with about 56-59%. Compared to oat wholemeal, carob fibre caused an increase in the rheological stability of the dough during mixing. This was indicated by the longer stability time, lower degree of softening and greater elasticity. Moreover, dough with carob fibre presented greater resistance to extension, but it was less extensible than dough with an addition of oat wholemeal. However, the fundamental difference in the rheological effect of the additions was that increase in the dose of carob fibre caused an increase in dough resistance, while increasing dosage of oat wholemeal caused weakening of that resistance. A common effect of both additions was a reduction in the extensibility of dough.

A rather novel approach to overcome some of the technological limits of incorporating higher amounts of oat in cereal products (i.e. the lack of gluten proteins to meet dough viscoelastic and fermentative restrictions) is high hydrostatic pressure treatment. This novel method studied by A. ANGIOLONI & C. COLLAR [15] seems to favour dough structure rearrangements in oat, among other grains, by altering the folding/unfolding and aggregation/disaggregation equilibrium of proteins enabling the use of high-pressure flours as gluten replacers. Restructuration of high hydrostatic pressure oat dough resulted in 60% oat – 40% wheat breads deserving better sensory scores and exhibiting higher antiradical activities than those prepared by a conventional breadmaking process and gluten incorporation.

A method more researched than high hydrostatic pressure is the addition of sourdough in the bread recipe. Sourdough is traditionally one of the ways to enhance bread flavour. Sourdough fermentation can also modulate the nutritional properties, such as increasing levels or bioavailability of bioactive compounds, and retarding starch digestibility. Sourdough may produce a significant reduction in the molecular weight of β-glucan. Sourdough of white wheat flour could provide lower endogenous enzyme activity and less degraded molecular
The weight of β-glucan in the product, especially if the oat is incorporated to the dough and not to the sourdough (L. FLANDER & al. [16]).

As the potential of sourdough to improve bread quality of oat-enriched wheat breads may depend on the characteristics of the added flour (cereal type, variety, extraction rate), A. RIEDER & al. [17] studied the effect of oat bran (substitution level 40%), unfermented and as sourdough (20% of total flour) on composite wheat dough and bread characteristics. Sourdough showed little effect on the breads prepared with oat bran. The breads made with oat bran showed highest bread volume, lowest crumb firmness and highest β-glucan calcofluor weight average molecular weight. The heat treatment of oat bran inactivated endogenous enzymes resulting in less β-glucan degradation. In the same study, results revealed a positive correlation between flour β-glucan content and bread β-glucan molecular weight on one side and bread volume on the other side. It was inferred that β-glucans by contributing to the viscosity of the water phase of the dough might have a potential to improve bread volume of composite wheat breads, if the water addition to the doughs is adjusted for the high water binding capacity of the β-glucans, like pointed out also by A. KTEINIOUDAKI & E. GALLAGHER [11]. As similarly suggested by L. FLANDER & al. [16], this study showed that apart from increasing the amount of β-glucan in the starting material, inactivation of endogenous flour enzymes might help to limit β-glucan degradation and ensure a high viscosity of the dough water phase.

L. FLANDER & al. [16] aimed to study the effects of sourdough fermentation of wheat flour with Lactobacillus plantarum, on the quality attributes of mixed oat-wheat bread (51 g whole oat flour and 49 g/100 g white wheat flour). The sourdough process was shown to be a feasible method for mixed oat-wheat bread, and provided bread quality equal to straight dough baking. A small amount (10 g/100 g dough) of slack sourdough fermented at high temperature (40°C) for a long time (20 h) resulted in the optimal sourdough bread with the highest specific volume (3.5 cm³/g), the lowest firmness after 3 days storage (0.31 kg), and low sensory sourness with high intensity of the crumb flavor. Maybe most importantly, wheat sourdough parameters did not affect the content of oat β-glucan in the bread.

Another method for development of oat dietary fibre enriched cereal products is the use of enzymes, which are regarded as clean label compounds. D.M. LEBESI & C. TZIA [18] treated oat bran with different levels (0, 70 and 700 ppm) of an endoxylanase enzyme and added this to cakes on 30% flour weight basis. It resulted that the water binding and holding capacity of oat bran were decreased while the soluble fibre content was increased. This enzyme treatment was found to be effective in reducing the initial crumb firmness and water activity and in increasing the batter viscosity, gelatinization temperature, specific volume, porosity and sensorial characteristics of the cakes. The optimum cake characteristics were obtained when oat bran treated with 70 ppm endoxylanase was used.

Extrusion presents various advantages as a food processing technique, in terms of low costs, speed, high productivity, versatility, unique product shapes, energy savings and good consumer acceptance. Yet incorporation of dietary fibre in extruded products often leads to reduced expansion volumes, higher densities, harder and less crispy textures that are less preferred by consumers. Because of these reasons, adding cereal fibres to extruded products has been limited to a maximum of 100-300 g/kg fibre substitution for flour. However, the negative effects of fibres in the extruded dough or products can be minimized if some additives are used (e.g. monoglycerides, modified starches, modified gelatine, oligofructose or inulin). L.P. LOBATO & al. [19] demonstrated the feasibility of producing an extruded ingredient with blends of oat bran, soy flour and maize starch in amounts of 375 g/kg, 375 g/kg and 250 g/kg, respectively. The best processing conditions to obtain good physical and sensory characteristics were 250 g/kg moisture and 160°C extrusion temperature. The
addition of 45 g/kg of inulin to the mixture was essential to impart flow to mixtures during extrusion. The obtained extruded product could be used as a granola or cereal bar ingredient or as a substitute for rice crispy as a snack with addition of flavors.

In the same time, soluble fibre provides higher expansion volumes while they affect less the bulk density of extruded products than insoluble fibre. F. ROBIN & al. [12] revealed that extrusion increased the solubility of oat bran fibre and it also increased its content of total and soluble β-glucan, as well as its total and soluble neutral sugars. Moreover, it was observed that the shear viscosity of oat bran, its shear thinning behaviours and its swelling capacity were increased after extrusion. The morphology of fibre was also modified during extrusion, as oat bran particle size reduces when the specific mechanical energy introduced during extrusion is increasing. Another study (M. ZHANG & al. [20]) revealed similar results, in terms of improving the functionality of soluble fibre in oat bran through extrusion. Compared with the soluble dietary fibre from untreated oat bran, soluble fibre from extruded oat bran was found to have more aggregates, higher gelatinization temperature, higher solubility, swelling capacity and solvent retention capacity, an increase in the apparent viscosity and consistency coefficient, a decrease in the flow behaviour index, and an improvement in foam ability.

A different challenge to be considered in developing oat-based products is having both a high nutritional value and good storage stability during freezing. For instance, in a study (I. MANDALA & al. [21]), the physical characteristics of frozen dough and semi-baked frozen samples for a mix of 40% whole oat flour – 60% wheat flour were determined after baking and comparisons to fresh samples were performed. The samples presented an increased water absorption capacity at high water activity, as observed by sorption isotherms and a water binding capacity change after storage. The semi-baked oat breads exhibited high crumb moisture content, low specific volume and soft crust.

**Current status of oats in gluten-free cereal products**

The increasing demand of higher-quality gluten-free products containing more nutritious cereals, like oats, represented a challenging task for the industry due to the low baking quality of gluten-free flours as a consequence of the absent gluten network. Another argument for the limited usage of oats in gluten-free diets was the risk of gluten contamination during harvest, transport, milling and/or processing (E.K. HÜTTNER & E.K. ARENDT [1]). Presently, new technologies are utilized to improve the production performance of gluten-free grains, while reliable analytical methods are employed for detection of oat purity intended for coeliac use in commercial products. Nonetheless, the latter was not the subject of this review.

Thus, the recent technological advances for the improved performance of oat flours in gluten-free products, some also pointed out by E.K. HÜTTNER & E.K. ARENDT [1], are: the addition of enzymes to promote protein networks formation (S. RENZETTI & al. [22], [23]; F. WANG & al. [24]), replacement of α-gliadins with coeliac-safe oat avenins (H.C. VAN DEN BROECK & al. [25]) and high hydrostatic pressure (E.K. HÜTTNER & al. [26]). Overall the aim of these studies was either to improve protein network formation or to increase the water absorption by proteins and starch, as products made from oats without added wheat require a different technology, oat doughs being more fluid than wheat doughs and closer in viscosity to cake batters.

S. RENZETTI & al. [22] investigated transglutaminase for network forming potential on flours from six different gluten-free cereals used in breadmaking, including oat. Transglutaminase was added at 0, 1 or 10 U/g of proteins present in the recipe (100 parts
flour, 125 parts of water, 2 parts of salt, 2 parts of sugar and 3 parts of dried yeast). Under the conditions of that study, no effects of transglutaminase could be observed on oat breads.

In S. RENZETTI & al. [23], commercial preparations of laccase and glucose oxidase, as well as of a protease were tested for their impact on the breadmaking performance of gluten-free oat flour. Laccase 0.1%, protease 0.001% and protease 0.01% additions significantly improved oat bread quality, as they increased specific volume and decreased crumb hardness and chewiness. Also, they decreased paste viscosity and improved paste stability. These improvements were explained by the increase in batter softness, deformability and elasticity, which were achieved upon addition of these enzyme preparations, both containing discernible levels of endo-β-glucanase side activity. On the contrary, glucose oxidase preparation was detrimental for the textural quality of oat bread by means of significant increase in crumb hardness. The formulation used consisted of 100 parts of oat flour, 89 parts of water, two parts of salt, two parts of sugar and three parts of instant dry yeast and, where applicable, an enzyme preparation.

In F. WANG & al. [24], oat dough containing 15% (w/w, blends of protein-oat flour basis) vital wheat gluten or 15% (w/w, blends of protein-oat flour basis) egg albumin was used to produce noodles with or without gluten. The rheological and noodle-making characteristics of oat dough containing exogenous proteins and the effects of added transglutaminase were examined. It was concluded that the properties of oat dough could be improved by the addition of transglutaminase and exogenous proteins.

The gluten proteins are composed of monomeric gliadins, responsible for the viscous properties, and polymeric glutenins, responsible for the elastic properties of the dough. Removing gliadins to fit gluten-free diets changes dough technological properties, causing an increase in stiffness of the dough. To investigate whether it is possible to compensate for the change in dough technological properties, H.C. VAN DEN BROECK & al. [25] tested the effects of adding oat avenins to dough from which gluten-encoding loci were removed to reduce T-cell stimulatory epitopes causing coeliac disease. It was concluded that oat avenins are a good alternative for wheat gliadins and could be added to the wheat flour that lacks coeliac disease stimulating gluten proteins, to improve or restore dough quality.

In E.K. HÜTTNER & al. [26], the effects of high hydrostatic pressure on oat batters were investigated. Oat batters were treated for 10 min at 200, 300, 350, 400 or 500 MPa. The results showed that high hydrostatic pressure significantly affected oat batter microstructure, and both starch and proteins were affected, improving batter viscosity and elasticity.

E.K. HÜTTNER & al. [27] also evaluated three commercial wholegrain oat flours from Finland, Ireland and Sweden for their breadmaking ability with the objective of finding predictive relationships between flour physicochemical properties and bread quality. It was concluded that in order to achieve high quality oat bread, whole oat flour should present the following properties: low batter viscosity, low flour water hydration capacity, starch content of above 65%, protein content of about 12%, low starch damage and coarse particle size.

Beside the improvements of the technological processes for higher quality products, the enrichment of gluten-free products with dietary fibre seems to be necessary since it has been reported that coeliac patients have generally a low intake of fibre due to their restrictive diet. In D. SABANIS & al. [28], among other cereal fibres, oat fibres were added at 3, 6 and 9 g/100 g levels into a gluten-free bread formulation based on maize starch, rice flour and hydroxypropyl methyl cellulose. Results showed that oat fibre could be added to gluten-free bread with positive impact on bread nutritional and sensory properties, in terms of significantly higher loaf volume and crumb softness compared to the control non-fibre gluten-free bread. Those breads also could provide consumers with higher amounts of total dietary fibre, had an appealing dark crust and a uniform and finely grained crumb texture.
M.A. GULARTE & al. [29] investigated the effect of soluble (inulin and guar gum) and insoluble (oat bran) fibres, added individually or in combination (replaced up to 20% of rice flour), to improve the functional properties of gluten-free layer cakes. The incorporation of fibres increased the batter viscosity, with the exception of inulin. fibre enriched gluten-free cakes containing blends of oat fibre and inulin resulted in improved specific volume. Significantly brighter crust and crumb was obtained in the presence of fibres, excepting the crumb of oat and guar gum containing cake. Fibres and its blends increased the crumb hardness, but the smallest effect was observed with the addition of oat, individually or combined with inulin. Fibres significantly affected the in vitro hydrolysis of starch fractions, the decrease in the slowly digestible starch being the most pronounced effect. Overall combination of oat fibre and inulin resulted in better gluten-free cakes.

Even though many research studies are focused on oat doughs for bread as most consumed cereal product worldwide, there are recent studies also centred on oat-based pasta (C. LAMACCHIA & al. [30]), noodles (C.L. CHOO & N.A.A. AZIZ [31]; F. WANG & al. [24]) or batters and cakes (D.M. LEBESI & C. TZIA [18]; M.A. GULARTE & al. [29]; E.K. HÜTTNER & al. [26]) that show relatively promising results. This comes to demonstrate the increased interest for developing new and diversified oat-based functional foods, with or without gluten, yet more research is needed in these areas. For instance, oat β-glucan enrichment affected the overall acceptability of noodles due to lower firmness, elasticity, surface smoothness, and flavour scores (C.L. CHOO & N.A.A. AZIZ [31]). On the other hand, F. WANG & al. [24] found that it could be possible to produce oat noodles either with or without gluten by the addition of transglutaminase and exogenous proteins.

Conclusions

Oat has a great potential as functional ingredient and its benefits to human health seem to go beyond the already approved health claims. Thus, it is likely that the number of oat-related claims could rise in the future, especially when technological advances are made for the production of high-quality gluten-free and composite cereal products with high amounts of oat. Nevertheless, extensive research is still needed in this area.

Whole oat appears to offer future opportunities. However limited information still remains on the health benefits of antioxidants from whole grains, like oats, and this is an area that warrants further investigations. Also, more research is required to better understand impact of whole oat flour on starch digestibility in vitro and glycaemic response. In A. RIEDER & al. [17], even though sourdough showed little effect on the breads prepared with oat bran, it improved the dough structure and bread quality of whole barley breads. Thus future research could investigate sourdough fermentation potential for the quality improvement of whole oat bread.

The literature review also revealed that hulless oat (Avena nuda) is less researched, even though there is evidence that the nutritional content is higher than in the common oats (A. KTENIOUDAKI & E. GALLAGHER [11]; S. ZILIC & al. [9]).

Like M.S. BUTT & al. [2] pointed out, the benefits associated with oats are achieved only when oat products are part of a daily diet for longer periods of time and the amount consumed overcomes certain threshold values. Thus, a future focus could be on how to obtain higher concentrations of nutrients in oat-based products in a way that does not lower consumer acceptance of such products. Endogenous enzyme inactivation could help to maintain high molecular weight β-glucans, which convey considerable health benefits in cereal products and should therefore be further investigated.
Further studies are required to fully understand the modifications brought by transglutaminase on cereal proteins and its potential to improve oat flour breadmaking, as this enzyme proved to be successfully applied (S. RENZETTI & al. [22]; F. WANG [24]).

Closing, it is essential to stress the importance of sensorial and consumer acceptance studies in new oat-based product development, as these functional products should be easy to include in the daily diets of consumers, so that the needed intake levels for the health benefits of oat to be reached. For instance, despite technological advances, two recent consumer studies (M. VASSALLO & al. [32]; N.E. HELLYER & al. [33]) suggest that consumers still perceive functional cereal products as common ‘staple’ foods, rather than as means of avoiding diseases, thus the expectations of no change in sensory characteristics of such products is rather high.

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