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Oats in healthy gluten-free and regular diets: A perspective

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ABSTRACT

During the 20th century, the economic position of oats (*Avena sativa* L.) decreased strongly in favour of higher yielding crops including winter wheat and maize. Presently, oat represents only ~1.3% of the total world grain production, and its production system is fragmented. Nonetheless, current interest is growing because of recent knowledge on its potential benefits in food, feed and agriculture. This perspective will serve as a further impetus, with special focus on the recently valued advantages of oats in human food and health.

Five approved European Food Safety Authority (EFSA) health claims apply to oats. Four relate to the oat-specific soluble fibres, the beta-glucans, and concern the maintenance and reduction of blood cholesterol, better blood glucose balance and increased faecal bulk. The fifth claim concerns the high content of unsaturated fatty acids, especially present in the endosperm, which reduces the risks of heart and vascular diseases. Furthermore, oat starch has a low glycemic index, which is favourable for weight control. Oat-specific polyphenols and avenanthramides have antioxidant and anti-inflammatory properties. Thus, oats can contribute significantly to the presently recommended whole-grain diet.

Next to globulins, oats contain a small fraction of prolamin storage proteins, called 'avenins', but at a much lower quantity than gluten proteins in wheat, barley and rye. Oat avenins do not contain any of the known coeliac disease epitopes from gluten of wheat, barley and rye. Long-term food studies confirm the safety of oats for coeliac disease patients and the positive health effects of oat products in a gluten-free diet. These effects are general and independent of oat varieties. In the EU (since 2009), the USA (since 2013) and Canada (since 2015) oat products may be sold as gluten-free provided that any gluten contamination level is below 20 ppm. Oats are, however, generally not gluten-free when produced in a conventional production chain, because of regular contamination with wheat, barley or rye. Therefore, establishing a separate gluten-free oat production chain requires controlling all steps in the chain; the strict conditions will be discussed.

Genomic tools, including a single nucleotide polymorphism (SNP) marker array and a dense genetic map, have recently been developed and will support marker-assisted breeding. In 2015, the Oat Global initiative emerged enabling a world-wide cooperation starting with a data sharing facility on genotypic, metabolic and phenotypic characteristics. Further, the EU project TRAFOON (Traditional Food Networks) facilitated the transfer of knowledge to small- and medium-sized enterprises (SMEs) to stimulate innovations in oat production, processing, products and marketing, among others with regard to gluten-free. Finally, with focus on counter-acting market fragmentation of the global oat market and production chains, interactive innovation strategies between customers (consumers) and companies through co-creation are discussed.

1. Introduction

Oat is more than just a common grain (Clemens & Van Klinken, 2014). It is transforming from a dietary staple for feed and food into a nutritive whole grain source as part of a healthy diet. Several health claims have been officially approved by European Food Safety Authority (EFSA) and USA's Food & Drug Administration (FDA). In cultivation, oat is a low-input crop that positively contributes to soil health especially in crop rotation systems by improving soil structure and reducing crop pests.

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Excavations from 32,600 years ago in Italy revealed the occurrence of thermally pre-treated and grinded oat grains (Lippi, Foggi, Aranguren, Ronchitelli, & Revedin, 2015). The cultivation of oat as a crop started much later than that of wheat and barley. It has been suggested that in the Bronze Age (5000–4000 years ago) common oat (*Avena sativa*) spread as a weed impurity of wheat and barley seeds from the Near East to Central and North Europe. Once arrived, oat turned out to adapt well to the cool and humid climate and long day length. The 'weedy' oat became domesticated in Europe by the early farmers into heterogeneous, robust landraces (Valentine, Cowan, & Marshall, 2011). Oat was appreciated as a perfect feed for working horses in agriculture. For that reason, it was often cultivated on-farm, and fitted well in the economy of small farming communities up to medieval times. Since then, oat became a major crop grown extensively in NW-Europe for feed, food and drinks. Oat was an important brewing cereal in the middle ages in NW-Europe (Meussdoerffer, 2009).

Starting from the early 20th century, horsepower was replaced by diesel engines, and oat beers were replaced by barley and wheat beers. These developments halved the global cultivation of oat. Now, also oat breeding is lagging far behind that of wheat and barley. Oat has become a neglected crop: the attention to the pureness of oat sowing seeds is limited. For example, the U.S. specification for No. 1 oats allowed the presence of up to 2% foreign material. Such a contamination could be wheat and barley (Webster, 2011), which is unacceptable in gluten-free food production.

Oat cultivation in The Netherlands dropped from 160,000 ha in the 1960s to 1200 ha in 2016. Presently, cultivation of oat is mainly for feed production and for (organic) food production. Current commercial yields are ~5.5 ton/ha. An increasing acreage is reported for gluten-free oat production. For the production of oats under gluten-free conditions, only strong-straw and short-straw varieties are being cultivated, to reduce the incidence of lodging, which may cause severe losses in yield (Tumino et al., 2017).

In order to realise oat's potential as a healthy crop in agriculture and as whole grain product in food and feed, and reverse the trend of decreasing production, we propose strategies for innovations in oat products (including specific focus on the gradually growing gluten-free market). A strengths and weaknesses analysis on the current position of oat regarding agronomy, processing, products and business (the successive steps in the production chain) is given in Table 1. These issues will be further elaborated in the paragraphs below.

It is expected that the specific appraisal of oats as versatile whole grain product in food and feed will lead to an increase in global production and application. Its unique food and feed characteristics, complemented with its advantageous agronomic characteristics, should, however, first be better recognized and higher valued globally to make oat an economically competitive crop again.

This perspective aims at answering the questions (1) why oats fit in a healthy gluten-free diet and (2) how (gluten-free) oats products might appeal better to consumers. We discuss the health advantages of oats in the general diet and in the gluten-free diet. We describe the requirements and conditions for gluten-free production of oats. We also address the current position of oats in the global food market, in the global food policy, and in traditional food networks, which is under threat as the global production of oat is mainly as a cheap and underrated source for feed applications.

2. The advantages of oats for health

2.1. Health claims

Oats have several health advantages (Martínez-Villaluenga & Peñas, 2017) and carries approved EFSA (Box 1) and FDA health claims for its positive effects on human health (Mathews, 2011). The health effects especially concern the hypocholesterolemic properties, the cardiovascular benefits through positive effects on the blood glucose level, and the improved management of body weight and blood pressure. In addition, consumption of oats is related to an increase of the faecal bulk. It contributes to a normal stool and maintenance of a balanced microbiome, which is attributed to the high content of soluble fibres, the oat-specific beta-glucans. Oats, therefore, fit perfectly in governmental (health council's) food strategies promoting the consumption of whole grain and cereal fibre, which has scientifically been shown to reduce the risks of chronic diseases and cause-specific mortality (Aune et al., 2016; Benisi-Kohansal, Saneei, Salehi-Marzijarani, Larijani, & Esmaillzadeh, 2016; Chen et al., 2016; Huang, Xu, Lee, Cho, & Qi, 2013; Wu et al., 2015; Zong, Gao, Hu, & Sun, 2016).

2.2. Primary metabolites and minerals

Oats are a good source of various antioxidants such as vitamin E, phytic acid, phenolics and avenanthramides (phenolic amine conjugates belonging to the group of secondary metabolites). Avenanthramides are less known oat-specific compounds (Collins, 2011) with anti-inflammatory properties (Liu, Zubic, Collins, Marko, & Meydani, 2004; Sur, Nigam, Grote, Liebel, & Southall, 2008). Avenanthramides synergistically with vitamin C inhibit LDL-cholesterol oxidation in vitro, they show antihistamine activity and may reduce allergy-related symptoms such as itching, redness and wheals. Formulations of natural colloidal oatmeal should be considered an important component in therapies for atopic dermatitis and other skin conditions, and may allow for reduced application of corticosteroids and calcineurin inhibitors (Cerio et al., 2010). Avenanthramides may also suppress the proliferation of vascular smooth muscle cells, a process known to contribute to atherosclerosis development (Liu et al., 2004).

2.3. Secondary metabolites

The primary metabolites of oat also contribute to nutrition and health. The coeliac-safe oat proteins (15–20% by weight), mainly globulins, are highly digestible and have an amino acid profile that fits very well to the human needs of essential amino acids, even with regard to lysine and threonine (Peterson, 2011). Oat starch (55% w/w) has an amylopectin/amylose ratio of about 3–4, with a complete and relatively slow digestion. In combination with the slow stomach emptying due to the fibre content, this gives a long feeling of satiety. Whole grain oat foods have a low glycemic index, which is advantageous in cases of diabetes and obesity (Mathews, 2011; White, 2011). Oat grains are high in oil content (on average 7%, but in some varieties up to 18% by weight) with large fractions of palmitic acid (C16:0; 20%), oleic acid (C18:1; 35%) and linoleic acid (C18:2; 35%)(e.g., Sterna, Zute, & Brunava, 2016). Alpha linolenic acid (C18:3, omega-3) is notably present in the germ (Lehtinen & Kaukovirta-Norja, 2011). The high oil content can have an adverse effect on the sensory quality as a result of oxidation (also known as rancidity). To prevent this, a kilning process (a short high-temperature treatment) of the oat grains is generally applied before further processing into food products (Londono, Smulders, Visser, Gilissen, & Hamer, 2015).

Welch (2011) gives a comparison of the composition of oats and oatmeal with that of several other cereal grains. Oatmeal has the highest content of several minerals, including phosphorus, iron, zinc and magnesium. The total beta-glucan content of oats is much higher than that of wheat (5 ×), maize (15 ×), brown rice (40 ×) or rye (2 ×), and comparable to that of barley. The solubility of oat beta-glucan is the highest compared to the other grains. Further, oat protein contains the highest levels of lysine, cysteine and methionine. Stewart and McDougall (2014) describe the composition of various compounds in relation to cultivation conditions.

Table 1
Strengths and weaknesses analysis of oats.

Oat	Strengths	Weaknesses
Agronomy	Millennia-long history as healthy and nutritious food/feed crop	Need for breeding of high-yielding, disease-resistant varieties, knowledge on genotype by environment (GxE) interactions
	Low input crop, fits well in organic agriculture	Sensitive to lodging, short straw varieties needed
	Soil quality-improving effects, fits well in several crop rotation systems	Up-to-date national and European cultivation manuals are required
		Limited knowledge on crop physiology, N-use, weed control, disease control
	High-quality gluten-free production chains have been developed	Strict protocols are required, obeyed and monitored to realise gluten-free cultivation and processing while avoiding contamination with wheat, rye or barley
	'Oat Global' is a pre-competitive open access database on phenotypic/ genotypic data. Genetic and genomic data are being developed.	Breeding is complex and time-consuming as oat is a hexaploid crop
Processing	Naked oat (*Avena sativa* ssp. *nudavena*) varieties available	Hulled varieties require de-hulling
	Kilning increases organoleptic quality (smell and taste)	High PUFA oil content: kilning required for shelf life and preventing rancidity
		Limited knowledge about effects of high fibre content on processing
		Limited knowledge about effects of processing (e.g. kilning, baking, extrusion) on health-related compounds (e.g. beta-glucans, proteins, avenanthramides)
Products	Immunogenic gluten are absent; oats are legally allowed to be sold as 'gluten-free' (EU, USA)	
	Five approved health claims for oat consumption and oat products for human health (see Box 2)	Limited use of health claims for marketing of oat food products, limited awareness and knowledge with the general public
	Recognized beer brewing grain in medieval times, currently regaining interest in special beers	
Business		Little attention for innovations in oat in the feed sector
		Fragmented market, lack of communication/co-operation between stakeholders along the production chain
	Younger generations embrace oats as health-food for each eating moment of the day, communication on internet and through recent cookery books	Product innovations are required
		Food- and agriculture-related policy gaps (potential role of oats in population health and sustainable agriculture is underdeveloped)

Box 1
Approved European Food Safety Authority (EFSA) health claims relevant to oats (EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA), 2010, 2011).

- Beta-glucans (3 g/day) contribute to the maintenance of normal blood cholesterol levels (EU 432/2012).
- Consumption of beta-glucans from oats and barley as part of a meal (4 g/30 g carbohydrates) contributes to the reduction of the blood glucose rise after that meal (EU 432/2012).
- Oat grain fibre contributes to an increase in faecal bulk (EU 432/2012).
- Reducing consumption of saturated fat contributes to the maintenance of normal blood cholesterol levels (EU 432/2012).
- Oat beta-glucan (3 g/day) has been shown to actively lower/reduce blood cholesterol. High cholesterol is a risk factor in the development of coronary heart disease (EU 1160/2011).

2.4. Health awareness

In all, the health-related values of oats surmount those of other grains. However, the awareness that whole grain oat products have the potential to positively impact many health-related conditions associated with coronary heart disease, diabetes, satiety/weight management (low GI), and blood pressure is still limited among consumers as well as in the medical field. The substantiated health claims may be helpful to educate the consumer, and should be brought to the attention of the public through targeted communication, advertisement and product labelling.

3. The general safety of oats in coeliac disease

3.1. General safety established

World War II, unintendedly, served as a big food intervention study. The shortage of bread in the winter of 1944 in The Netherlands improved the condition of some children with specific bowel and growth problems, which quickly reversed after airplanes of the Allied Forces dropped wheat bread loafs and boats brought in wheat flour. This assisted the discovery of wheat, and especially its gluten, as the cause of coeliac disease (CD; Dicke, Weijers, & Van de Kamer, 1953; Van de Kamer, Weijers, & Dicke, 1953). Initially, CD-causing gluten was thought to originate from wheat, barley, rye and oat. In the 1990s, several studies demonstrated that CD patients could tolerate oats without signs of intestinal inflammation. There is now sound scientific evidence that CD patients can regularly eat up to 100 g/day of uncontaminated oats without any harm (Hardy, Tye-Din, & Stewart, 2015). This confirms long-term cohort studies of CD patients regularly eating oats, among others in the Nordic countries (Janatuinen et al., 1995; Kaukinen, Collin, Huhtala, & Mäki, 2013; Pulido et al., 2009; Tapsas, Fälth-Magnusson, Högberg, Hammersjö, & Hollén, 2014). The study of Kaukinen et al. (2013) concluded that "the mucosal morphology was even significantly better in CD patients who had consumed oats in larger amounts or over a longer time-period than in those who did not take oats". They also concluded that "it was impossible to trace which cultivars were used, as the patients were able to use a wide range of commercial oat products from the market. This notwithstanding, the patients remained in clinical and histological remission." Aaltonen et al. (2017) compared health and well-being of celiac patients on a gluten-free diet with or without oats. The median duration of the gluten-free diet was 10 years and 82% consumed oats. They concluded that long-term consumption of oats in celiac disease patients is safe and may improve the quality of life. In their meta-analysis of clinical studies, Pinto-Sánchez et al. (2017) found no evidence that addition of oats to a gluten-free diet affects symptoms, histology, immunity, or serologic features of CD patients, although they would like to see more well-designed randomised trials, using commonly available oats sourced from different regions.

3.2. An exception

In a Norwegian study, 19 adult CD patients on a gluten-free diet were challenged with 50 g of oats per day for 12 weeks (Lundin et al., 2003). Before and after this open challenge, serological testing, histological biopsy scoring, and interferon gamma mRNA determination were carried out. Oats were well tolerated by all patients but one who developed subtotal villous atrophy, also after a repeated oat challenge. This patient had developed mucosal T cells that showed aveninreactivity in vitro. Using these T cells, two avenin epitopes were identified with only one amino acid difference: PYPEQEEPF and PYPEQEQPF. Although this case was considered exceptional, it was suggested that oat intolerance may exist (Arentz-Hansen et al., 2004). This study had a long echo and created doubt about the safety of oats in general, which is further incorrectly propagated by studies based on clinically irrelevant cross-reactivity in oat testing using antibodies raised against specific wheat gluten epitope sequences (reviewed in Gilissen, Van der Meer, & Smulders, 2016b). The Norwegian study has not been confirmed by other studies on CD patients although it is likely that, rarely, more patients may exist that react to oats (Lundin, personal communication).

3.3. Gluten-free oats

The seed storage proteins of oat are dissimilar from those in wheat, barley and rye and do not contain immune-active fragments that may lead to the development of coeliac disease (CD) in genetically predisposed individuals (Londono et al., 2013). Since 2009 in Europe, since 2013 in the USA, and since 2015 in Canada oat products may be sold as gluten-free provided gluten contamination from wheat, barley and rye is below 20 ppm. However, several factors hinder gluten-free oat production. Batches of oat grains are generally contaminated with gluten-containing cereals (wheat, barley and rye) (Thompson, 2003, 2004; Thompson, Lee, & Grace, 2010; Webster, 2011). Volunteer grains of gluten-containing cereals may remain in the cultivation soils and in organic manure, while dragging of gluten may occur in grain mills and in factories during further processing. A small amount of contamination with gluten-containing grains (a few kernels per kilogram) already leads to gluten levels far above 20 ppm. Therefore, specific agronomic and production requirements should be met throughout the entire oat production chain when gluten-free oat products are the aim (see below).

3.4. Improving the nutritional quality of the gluten-free diet

In view of the health benefits, inclusion of oats in the gluten-free diet has many advantages for CD patients in particular, but also for people who follow a gluten-free diet for other reasons. Oat consumption is now advocated as part of the gluten-free diet, as current gluten-free products, made without wheat, barley or rye, have a low content of vitamins, minerals, and especially fibres, are high in starch and salt, and contain more saturated fats and many additives, resulting in products that are less healthy than gluten-based equivalents (Gobbetti et al., 2017; Jouanin et al., 2018; Lamacchia, Camarca, Picascia, Di Lucci, & Gianfrani, 2014). Oat consumption improves several aspects of the gluten-free diet, such as adding minerals but reducing salt (thus better regulating blood pressure), and increasing the unsaturated fatty acids content, in addition to its regular health advantages (see also Box 1 on approved EFSA health claims). It also diversifies the diet, and patients appreciated its taste (Peräaho et al., 2004).

4. Gluten contamination as major cause of immunogenicity

4.1. Gluten contamination threshold in legislation

The Norwegian study was no reason for European and US governments to discourage the consumption of oats by people with CD. The large pile of publications showing the safety of oats in cases of CD was sufficiently convincing to the regulatory bodies. In January 2009, EC-Regulation 41/2009 on the content and labelling of foods for individuals with CD, came into force in Europe. Oat products containing < 20 ppm gluten are now allowed to be sold as gluten-free and may carry the official logo of the AOECS (Association of European Coeliac Societies) on a contract basis and subjected to a regular audit of the producer. Since August 2013, also the USA (www.federalregister.gov) allows oats to be sold as gluten-free, provided contamination with gluten from wheat, barley and rye is below 20 ppm. According to their Food Standard Code, Australia and New Zealand are still reserved, but this may change rapidly soon since a consortium of Australian researchers has concluded that doses of oats commonly consumed are insufficient to cause any clinical relapse (Hardy et al., 2015). In 2016, a Canadian position paper also concluded that oats uncontaminated by wheat, barley and rye can be safely ingested by most CD patients and that there is no conclusive evidence that the consumption by CD patients of uncontaminated or specially produced oats containing no > 20 ppm gluten, should be limited to a specific daily amount. They advise to introduce uncontaminated oats in the gluten-free diet after all symptoms of CD have resolved (La Vieille, Pulido, Abbott, Koerner, & Godefroy, 2016).

4.2. Gluten contamination in food products

Today, the problem for CD patients in consuming conventional commercial oats and oat products is their frequent contamination with gluten from wheat, barley and rye. A Canadian study from 2011 confirmed that the conventional commercial oat supply is heavily contaminated with gluten from other grains: 88% of regularly produced oat samples were contaminated above 20 ppm gluten (Koerner et al., 2013). A large investigation into the extent of gluten cross-contamination of naturally gluten-free flours and starches showed that almost 10% of the samples were contaminated above 20 ppm gluten. It concerned especially the higher fibre ingredients derived from naturally gluten-free sources such as soy, millet, buckwheat and flax. If these ingredients are not produced under gluten-free conditions, they may become sources of gluten contamination during gluten-free food processing (Koerner et al., 2011). Therefore, the cultivation and processing of gluten-free foods should be restricted to gluten-free certified farms and factories only (Fritz, Chen, & Contreras, 2017; Gilissen, Van der Meer, & Smulders, 2014). An unambiguous gluten detection system is an indispensable requirement.

4.3. Gluten detection

Detection of gluten contamination is mostly carried out using ELISA technology. The R5 (R-Biopharm) and the G12 antibody-based tests may, in some cases, cross-react with oat avenins and thus are not ideally suitable for the detection of gluten contamination of oat samples, in contrast to the DQ2.5-glia-α3 antibody (Gluten-TEC®) test (Gilissen et al., 2016b; Londono, Smulders, Visser, Gilissen, & Hamer, 2014; Sajic et al., 2017). Erkinbaev, Henderson, and Paliwal (2017) explored the use of near infrared spectroscopy to inspect grains for quality control during gluten-free oat processing. Also GC-MS and DNA-related tests are under development for the detection of possible contamination with wheat, barley and rye in gluten-free foods. To date, the Gluten-TEC® test seems to be the most appropriate to unambiguously demonstrate any possible gluten contamination in gluten-free produced oats products.

5. Strictly controlled gluten-free oat production chains

In several countries (e.g. Finland, The Netherlands, Ireland, Canada) gluten-free oat production chains have been established that meet very strict requirements regarding gluten-free conditions (according to HACCP (Hazard Analysis Critical Control Points) and EHEDG (European Hygienic Engineering & Design Group) standards). In the Netherlands a gluten-free oat production chain has been established since 2011. A test period of five years has resulted in a list of strict conditions for gluten-free production (Box 2). Similarly, strict production rules are in place in Ireland. In the USA and Canada several oat processors operate under a ‘Purity Protocol’ with a set of production rules (described in Allred et al., 2017).

Box 2
Conditions for gluten-free oat production as used in the Dutch gluten-free oat chain. Strict rules for gluten free oat cultivation and processing management.

- The farmer is certified for the gluten-free cultivation of oat and has not grown and worked up wheat, barley or rye during the preceding eight years on his farm.
- Oat sowing-seed is produced by a certified seed company and is guaranteed pure, i.e. the sowing seed is free from kernel-based contamination with grains of wheat, barley and rye, and is certified as such.
- No use of organic manure is allowed to prevent the occurrence of manure-derived volunteer plants of wheat, barley and rye in the oat cultivation field.
- No wheat, rye or barley has been grown on the oat cultivation parcel in the eight preceding years
- Official registration of the oat cultivation regarding location, variety, area (ha), yield, and delivery is done.
- The oat cultivation area is sufficiently separated (> 75 m) from gluten-containing cereal cultivation fields.
- The oat cultivation is at least three times inspected on occurrence of wheat, barley, rye volunteer seedlings/plants starting from three weeks after sowing.
- The cultivated oat variety is in agreement with the customer.
- The machines for sowing, harvesting and further seed treatments are carefully cleaned.
- The transport and storage of gluten-free produced and harvested oat grains occur in clean boxes or bags or equivalent covered containers.
- Mycotoxins are analyzed on the grains produced; when legal mycotoxin thresholds (200 μg/kg oats for HT-2 plus T-2 (EC/2013/165), 750 μg/kg DON in oats for human consumption (EC/1881/2006)) are surmounted, the batches are withdrawn from further processing to marketable products.
- Delivered grains and further processed intermediate products to customers (before the final packaging and marketing) are fully traceable; the oat ingredients of the end products are traceable to the consumer back to the field/plot level.
- At each change of customer in the production chain, a standardized gluten detection test is carried out by intake and documented.
- Eventual complaints on the product are registered; measures are taken for improvement.
- The production of oat-based foods is only allowed in GF-certified companies/factories.

The established Dutch Gluten-free Oat Chain follows a no-contamination strategy at each step in the production and processing of oats. The Chain includes a seed company that draws up the contracts with the farmers about the cultivation conditions and the price to earn. The seed company produces and distributes the pure sowing seeds. A breeding company is involved to develop new oat varieties with desired traits to be further multiplied by the seed company and to be delivered to the farmers. The seed company advises the farmers and is involved in the regular field inspections during cultivation. The oat grains harvested are transported under strict conditions to the seed company and are batch-wise controlled by eye for possible kernel-based contamination with wheat, barley, or rye grains. Batches that are nevertheless contaminated above the threshold of one kernel of wheat, barley or rye per kg oat kernels (although this corresponds with a < 5 ppm gluten contamination), are nevertheless rejected and transferred to the common oat market. Then grains may be stored in clean and dry storage facilities or are directly disposed of dirt and possibly occurring weed seeds, and de-hulled before transport to the next step in the chain, the purchasers of the grains. These include the gluten-free grain crusher who will produce breakfast cereal products and bring these on the market directly and the gluten-free miller who will produce oatmeal and oat flour. These meals and flours will further be transported to the gluten-free baker for making oat breads. At each change of customer, a gluten detection test is carried out at intake. Gluten-free oat products from this production chain are now on the Dutch and international market since 2011. Because of the strict maintenance of the conditions for cultivation and further processing and production, no product recalls have been needed up to now.

6. Breeding, genomics and cultivation of oat

Along with the decrease in cultivation of oat during the 20th century, oat breeding lagged behind the breeding efforts in the major cereals maize, barley and wheat, so that now the average yield of oat is lower and the production risks are higher, e.g. because of lodging. This makes cultivation of oat increasingly less attractive to farmers. In recent years the advances in genomics have made it possible to rapidly generate the tools required for marker-assisted breeding to improve new oat varieties in various qualitative aspects and with regard to resistance to various diseases (Stewart & McDougall, 2014). These tools include a consensus genetic linkage map of the hexaploid oat genome (Oliver et al., 2013), expanded by Chaffin et al. (2016) and available at the public oat database 'T3/Oat' (https://triticeaetoolbox.org/oat/). A single nucleotide polymorphism (SNP) marker array has been developed (Tinker et al., 2014). Yan, Bekele, Wight, et al. (2016) established the ancestral relationships of the chromosomes of hexaploid oat and the relationships among 27 Avena species, using high-density genetic markers. Genome-wide association studies recently provided insight in the structure of germplasm and the genetic basis of variation in various traits (Winkler et al., 2016) including beta-glucan content (Asoro et al., 2013), heading date (Klos et al., 2016), frost tolerance (Tumino et al., 2016) and sensitivity to lodging (Tumino et al., 2017). Also the genetic basis behind the naked trait of oat (*A. sativa* ssp. *nudisativa*) is being elucidated (Ubert, Zimmer, Pellizzaro, Federizzi, & Nava, 2017).

Herrera, Gao, Vasanthan, Temelli, and Henderson (2016) tested eight oat varieties on 20 locations in Canada for three years, and determined their composition. They found that the beta-glucan content was primarily influenced by the oat cultivar grown, and hardly by growing location. Chappell, Scott, Griffiths, et al. (2017) tested oats cultivated in Orkney for macronutrients and minerals, and saw differences among the six varieties and also among years. In the Netherlands, fifteen ancient and modern oat varieties (including some naked varieties) were cultivated conventionally in an experimental setting on clay and sandy soil during five subsequent years in order to perform biochemical testing and further selection for their (gluten-free) bread baking potential (Londono et al., 2014; Londono, Gilissen, et al., 2015; Londono, Smulders, et al., 2015). In ten varieties the presence of health-related compounds were analysed in relation to soil type (Van den Broeck et al., 2016). Principal component analysis demonstrated clear effects of the genetic background on all components with significant additional soil effects on protein, starch, beta-glucan fibres, and antioxidants. Such analyses are helpful in profiling oat varieties for specific (nutritional and health) purposes. All tested varieties suffered from lodging, especially when cultivated on clay soil and in years with high rainfall and heavy wind during the second half of the growing season. Next to yield loss, lodging enhanced fungal growth in the crop and promoted the production of mycotoxins. Deoxynivalenol (DON) was present above the European threshold in all clay soil-grown and lodged varieties in 2011. HT-2 was found in two of these varieties and T-2 in one variety. DON values on sandy soil remained far below the European threshold. On clay as well as sandy soils, the values of HT-2 and T-2 were low and far below the European legal threshold. Spraying with fungicides repressed fungal growth (Timmer & Kamp, 2013). Short-straw varieties appeared to have a great advantage. Also the application of a growth regulator (Moddus (at 0.4 L/ha)) considerably reduced lodging damage in the high lodging-sensitive variety Gambo. In addition, Moddus also resulted in increased experimental grain yields on small plots of up to approximately 10–15% (estimated at 9.3 tons/ha) (Timmer & Kamp, 2013).

7. Gluten-free oat production and products as niche markets for SMEs

7.1. Oat Global

Oat's economic relevance has been decreasing for decades. As a consequence, the global oat production system has become highly fragmented, and fragmentation hampers economic growth, development and strength. To reverse such a situation, strategies must be developed (Gilissen et al., 2016a) regarding: (1) transfer of knowledge to fill identified knowledge and expertise gaps; (2) coordination to align policies of various actors, e.g. through the development of an integrated global oat cultivation and management manual building on local expertise; and (3) cooperation to realise and implement specific policy aims regarding the successive steps in the production chain from 'Primary production', 'Processing', 'Products' and 'Business' on oats towards a global oat chain. The establishment of the Oat Global initiative (www.oatglobal.org) is a promising step in this regard. This initiative represents a new strategy platform for the oat community. It emerged as a grass-root initiative of private millers and public leaders in the North American, Latin American, European and Australian oat community. Oat Global aims at housing and sharing many data sets on genotypic, metabolic and phenotypic characteristics to the global oat scientific community. This is an important step towards a global view and approach on oats.

7.2. TRAFOON

Transfer of knowledge is especially relevant to small and medium sized enterprises (SMEs). SMEs in the food sector are increasingly under pressure due to developing open markets, increasing demand for standardized and price-competitive food products by consumers, rising prominence of large retailers, and challenges from governmental regulations. These factors raise risks of losing many traditional foods as well as traditional processing technologies, which are applied by SMEs using regional raw materials. Traditional foods often have a role in the cultural identity of regions and there is growing consumers' interest in traditional, local and organic food products. To reach these markets, SMEs producing traditional foods must extend their skills in modern as well as competitive marketing strategies and production techniques to comply with EU regulations and to promote the aspects of their products related to nutrition and health. Modern production and processing techniques should be implemented while safeguarding the traditional qualities of the product and technology (requiring redevelopment of skills, e.g. in sourdough processing and brewing) (EuroFIR, 2005; Grunert, Jensen, Sonne, Byrne, & Clausen, 2008). The EU project TRAFOON (Traditional Food Network to improve the transfer of knowledge for innovation, 2013–2016) (https://www.trafoon.eu/) was established to support SMEs through network development, among others in the grain sector, with oat and its gluten-free food production as major targets. World-wide, the market for gluten-free products steadily increased during the last decade. TRAFOON developed an 'Inventory of needs' based on questionnaires to SMEs involved in various steps of the production chain, including the Dutch gluten-free oat production chain. In addition, within the framework of TRAFOON, the Oats2020 conference (in Birmingham in 2015; www.oats2020.org) was reviewed, as well as volume 112 of the British Journal of Nutrition that was entirely dedicated to oats. The 'Needs' identified in the 'Inventory' and the other sources have been collected and translated into a Strategic Research and Innovation Agenda that has been submitted to the European Commission (in autumn 2016). The needs were categorized according to the production chain.

- The needs of 'Primary production' included an updated oat cultivation manual, the inclusion of more genetically diverse germplasm (i.e. old varieties and wild oat species in breeding programs), and the integration of genomics and genomics-based strategies, including high-throughput phenotyping, in oat breeding. Meeting these needs may be helpful, among others, to bridge the yield gap with other, more profitable cereals. These issues are complex due to the allopolyploid composition of cultivated oat. Here, the Oat Global initiative is relevant.
- Concerning 'Processing', there appears to be limited knowledge about the impact of processing on nutritive and health values in general, although extrusion may increase health functionality of soluble fibre (Honcu et al., 2016; Zhang, Bai, & Zhang, 2011). This knowledge is needed for further development and substantiation of health claims for end products. One knowledge gap concerns the impact of oat consumption on the gut microbiome in humans and animals.
- To further improve the image of oats, 'Product' innovations are indispensable, so that oats may be consumed in many different types of products, including e.g. oat bread (Londono et al., 2014, Londono, Gilissen, Visser, Smulders, & Hamer, 2015). Here, *innovation* should get priority over *traditional*. The general consumer's awareness on the health advantages of oats is low and the societal role of oat consumption with regard to preventing chronic diseases is underrated. Reducing health care costs through improved food choices and consumption will be accelerated through interdisciplinary research and cooperation in local and global food policies: oats can play a role in this. This area opens plenty of space for international food industries, but the most interesting niches are available for the innovative and specialized food SMEs. Technical, taste, and flavor solutions need to be developed to produce healthy food products that meet consumer needs (Marais, 2017).
- These open niches open many ways for 'Business' on oats. Because of its potential in small markets, oat lends itself to the development of (gluten-free) production chains in which the customer and the consumer both can play an active and interactive role, e.g. through 'co-creation'.

7.3. Gluten-free oat products developed in co-creation

One way of addressing reversion of fragmentation of the oat chain could be co-creation, an interactive innovation strategy between consumers and companies, in which the use of social media can play an increasingly important role. Over the past decades new perspectives have emerged on processes aiming at product innovations for current and new markets, moving from a 'market push' system into a production strategy in which consumers' needs and behaviour are taken into account (Vargo & Lusch, 2016). The level playing field for this innovation is interaction, which may reduce the current paradox between growth and value creation by companies on the one hand and dissatisfaction of consumers on the excessively grown choices of products and services on the other hand (Prahalad & Ramaswamy, 2004). Co-creation in its optimum form is characterized by dialogue, common ground, enthusiasm, action power and a clear focus on the end result, and is based on equivalence of the partners, mutuality, sincerity and trust. Stakeholders can be involved in several ways at different levels, dependent on the desired or chosen input determined from the initiator's perspective.

One of the stakeholders groups that such developments could involve is young people; this could be done in more personal and individual ways and could move them towards innovative food production strategies, including co-creation. A recent trend under adolescents and 'Generation Y' (millennials) is towards the consumption of healthy foods, although 'health' is not always defined based on (scientifically substantiated) advices from national and international (e.g. WHO) food and health councils. These councils promote the consumption of sufficient food fibre from whole grains. The younger generation with their rapidly increasing communication through social media seems to adopt such food and life strategies and they include oats in their daily diets. Innovative oat recipes, also in gluten-free settings, for each eating moment of the day can now be found on internet and have been published in appealing cookery books (Bonnier & Kok, 2014).

Another stakeholder group is the Coeliac Societies present in most western countries, often associated in larger organizations, e.g. the AOECS (Association of European Coeliac Societies), with many active members. Most national Societies have their own magazines in which the rapidly increasing number of gluten-free food producers, mostly at the level of SME, are advertising their products. These magazines form the level playing field to initiate co-creation in the development of gluten-free healthy oat-based foods.

8. Conclusions

Whole-grain oat products have a positive impact on many health-related conditions associated with coronary heart disease, diabetes, satiety/weight management, intestinal functioning, and blood pressure. The substantiated health claims may be helpful to educate the consumer, but they have to be brought to the attention of the public through targeted communication, advertisement and product labelling. There is also a need for oat product innovation. Such innovations should, however, go hand in hand with filling the lack of knowledge about the impact of processing on nutritive and health values. This knowledge is required for further development and substantiation of health claims for oat-based end products. Regarding the coeliac population, oats uncontaminated by wheat, barley and rye can be safely ingested by most coeliac patients, with the major advantage of improving the nutritional quality of the gluten-free diet. With regard to increasing oat cultivation and use for human nutrition, co-creation with active involvement of both companies and consumers to develop and introduce new oat-based products, and the application of social and conventional media may contribute. This may support a more prominent role for oats in the global food policy.

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Conflicts of interest

Bert-Jan van Dinter is director of seed company Vandinter Semo but the company did not contribute financially to the realization of the paper. The authors declare no conflict of interest. The sponsors had no role in the collection, analyses, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results.

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