How can both the health potential and sustainability of cereal products be improved? A French perspective

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ABSTRACT

A more sustainable cereal sector would preserve the environment (environmental sustainability) and promote health (physiological sustainability) at a price that is acceptable to consumers regardless of their social status (socio-economic sustainability). The health potential of cereal products can be improved throughout the cereal sector via a more integrative approach based on reverse engineering. Globally, whole-grain products that contain less sugar, fat and salt must be developed. Therefore, the first main point is to fully understand the consumers’ acceptance of such new cereal products of higher nutritional value. Then, levers and locks at the technological, agricultural and genetic selection levels must be identified. Recent literature reviews and Committee reports emphasised the importance of preserving the structure of cereal foods via less drastic hydrothermic and mechanical processes and greater use of pre-fermentation and/or germination processing. The results of more human intervention studies are required to fill the gap between those obtained from observational and mechanistic/animal studies, notably, in reaching a conclusion regarding the health-promoting antioxidant potential of whole-grain cereal products. However, genetic selection faces the constraints of preserving both high yields and high levels of protective bioactive compounds. In conventional agriculture, one important issue is the accumulation of pesticides in the outer fractions of grains, which affects the development of whole-grain products. Although organic agriculture does not seem to provide a significant improvement in nutritional value, this practice is clearly more sustainable in terms of environmental protection. In conclusion, the improvement of the nutritional value of cereal products in the framework of a sustainable development should involve the concerted contribution of different actors of the sector.

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1. Introduction

Certain practices affect the nutritional quality of cereal products, including the refining and fractionation processes applied to the raw material and the addition of sugar, salt and fat in product formulations. During refining, the components of high-nutritional value that are contained in the bran and germ fractions, such as fibre, micronutrients and protective phytochemicals, are stripped from the grains; whereas the addition of salt, sugar and fat causes public health problems, such as the increased prevalence of obesity, type 2 diabetes, cardiovascular diseases and cancers. A typical example is childrens’ breakfast cereals, which are usually made from refined grains (with very few protective micronutrients) that are extruded under stringent conditions (causing a high glycaemic index) and are high in sugars and fats (risk factors for the development of overweight and obesity) (Lioger et al., 2007).

In addition to addressing problems caused by the accumulation of contaminants (including mycotoxins and insecticidal residues) in the outer layers of the grain, the proponents of non-refining or less intensive refining must also address the question of the acceptability of whole-grain and partly refined flours from digestive and taste perspectives. The challenge for the cereal sector is to maintain the organoleptic properties and safety of cereal products while improving their nutritional quality.

With the objective to develop sustainable diet, several questions must be addressed at the different levels of the cereal sector, as follows: 1) at the level of agricultural production, can we select genetic varieties that are the richest in protective micronutrients or use cereal varieties that are very little cultivated currently but are rich in the nutrients of interest while maintaining a satisfactory yield? Can we use cultivation practices that are more protective of the environment and at the same time ensure the nutritional value...
of cereals? Are the increased yields necessary to feed a growing population compatible with maintaining a satisfactory level of protective micronutrients? 2) At the level of first transformation, what degree of flour refining should be achieved to maintain both good acceptability and good nutritional quality of cereal products? Can we generalise the techniques for isolating the aleurone layer (rich in lysine and protective micronutrients but also in potential allergens) and systematise the fortification of grain products using this fraction (Bröns et al., 2012; Hemery et al., 2007)? How can we make better use of the germ fraction? 3) At the level of the second transformation, can we develop “softer” technologies for formulating grain products? Can we reduce the levels of sugar, salt and fat from a technological point of view (Poutanen et al., 2014)? 4) In terms of consumption, are consumers’ tastes likely to evolve toward cereal products that are less refined and are less rich in sugar, salt and fat than current cereal products? In other words, a more sustainable cereal sector must preserve the environment (environ- rnal sustainability), human health (physiological sustain- ability) and cultural habits (cultural sustainability) at a price that is acceptable to the consumer regardless of his or her socio-economic status (socio-economic sustainability).

The main objective of this review is to discuss the possible improvements in the health potential of cereal products that could be made throughout the entire sector, from “field to plate” by adopting a more holistic and integrative perspective.

2. State of the art and current investigations

What is known about the health potential and health effects of grain products? This topic has been thoroughly covered by many reviewers (Björck et al., 2012; Borneo and Leon, 2012; Fardet, 2010; Frelich et al., 2013; Gibson et al., 2013; Poutanen, 2012). Based on a recent review of the literature, the issues described below deserve emphasis in future study.

2.1. Health effects of whole-grain versus refined cereals and of highly versus slightly processed cereal products

Overall, whereas the regular high consumption of more or less whole-grain products is associated with a lower prevalence of overweight/obesity, type 2 diabetes, cardiovascular disease and certain gastrointestinal cancers, the reverse was observed for the consumption of refined grain products — although there are fewer studies of the latter — and many studies have shown only a lack of association (Fardet and Boirie, 2014). For example, a recent meta-analysis showed a significantly higher (+27%) prevalence of type 2 diabetes in the highest consumers of white rice (Hu et al., 2012). The same result was obtained in a previous pooled analysis (17%), which also showed that the prevalence of type 2 diabetes was significantly lower among the highest consumers of unrefined brown rice (−11%) (Sun et al., 2010). The protective effect vis-à-vis type 2 diabetes could be more related to the bran fraction rather than the germ fraction (Sun et al., 2010).

Concerning intervention studies, all researchers agreed that there is a great need for more studies to identify a direct causal role of phytochemicals in the metabolic health benefits of whole-grain cereal and in their ability to mitigate the progression of chronic diseases (Belobrjadic and Bird, 2013; Giacco et al., 2011; Smith and Tucker, 2011). For example, the high antioxidant potential of cereal products as measured in vitro has not been convincingly confirmed in vivo in humans (Fardet et al., 2008; Price et al., 2012).

Refining grains causes considerable losses of the micronutrients, phytochemicals and fibre fractions that are concentrated in the bran and germ (Fardet, 2010). For example, refining wheat flour at less than a 70% extraction rate causes the loss of 60–90% of the B vitamins (Laerke and Knudsen, 2011). The considerations for flour refining, other than the considerable reduction of the content of phytochemicals, involve the amount of fibre, which is contained mainly in the outer layers, and which is also important because numerous phytochemicals are associated with the fibre fraction, i.e., they are “fibre co-passengers” (Fardet, 2010; Jones, 2010; Laerke and Knudsen, 2011; Vitaglione et al., 2008). Increasing the fibre intake is strongly encouraged as part of the recommendations of the French Programme National Nutrition Santé (PNNS) (Ministère du Travail, de l’Emploi et de la Santé, 2011). Thus, there is a strong temptation to systematically enrich refined cereal products with fibre extracts rather than using more wholemeal flours. However, whether or not the fibre extracts are as beneficial to health as the fibres that are natural components of the whole grain remains largely unexplored. Adding fibres may be a solution that would reduce the gap between the recommended intake and the actual fibre consumption. However, fibre isolates generally lack the phytochemicals present in whole grains that can provide additional potential health benefits (Smith and Tucker, 2011). In addition, the health implications of the widespread use of fibre extracts are not clear (Laerke and Knudsen, 2011).

Regarding the salt, refined fat and sugar that are added to cereal products, the health effects are more obvious; too much salt intake can cause hypertension, whereas the excessive intake of sugars and fat is a risk factor for cardiovascular disease, obesity, type 2 diabetes and certain cancers. Incidentally, the presence of rapidly bioavailable sugars in very refined and processed cereal products is also a risk factor for the development of type 2 diabetes. However, the addition of salts is primarily an issue for the baking industry, with bread being one of the main sources of added salt in France (i.e., ≈ 25% of total daily consumed salt) (Afssa, 2002), and the addition of fats and sugars is relevant mainly for the biscuit and breakfast cereal industries.

2.2. The importance of the physical structure of cereal products

The physical structure of grain products is increasingly recognised as a parameter governing the health benefits of whole-grain products because it affects the prolonged feeling of satiety (limiting snacking between meals) and the gradual release of nutrients, including that of glucose from the digestion of starch, such as in the case of pasta (Fardet, 2010; Fardet et al., 1998, 2013). Although cereal grain processing is indispensable for producing the final physiological and health effects (Frelich et al., 2013), highly processed grain products generally have a less compact physical structure and therefore are less satiating (Abou Samra et al., 2008; Isaksson et al., 2011, 2012); for example, minimally processed low-glycaemic index (GI) muesli-type breakfast cereals are more satiating than highly processed extruded high-GI breakfast cereals (Brand-Miller et al., 2002). However, optimising the satiation effect is not sufficient if acceptability and enjoyment are not achieved (Villemejane et al., 2012, 2013).

2.3. Can behaviours be changed?

Around the issues regarding wholemeal flours and more particularly the issue of reducing sugar, salt and fat contents, the acceptability of products by consumers is important. Some recent surveys provided insight into the acceptability of less refined grain products. In the first survey, Saulnier and Micard reported: “The criteria for consumer preference are not always compatible with the technological innovations developed to meet the nutritional recommendations” (page 7) (Saulnier and Micard, 2012). For example, introducing fibre to French baguette reduced their visual acceptability, and acceptability after tasting was

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preserved only for certain products, e.g., French traditional baguettes. Second, as part of the HealthGrain project, a survey of the health and hedonic expectations of consuming bread, pasta and biscuits made from whole-grain or refined flour was conducted among consumers in Germany, Finland, Great Britain, and Italy (Shepherd et al., 2012). The results showed that there was a difference in perception among the consumers from different countries, for example, the health benefits of whole-grain products are highly apparent in Finland while quite a few of them in Italy are hardly known. Globally, women and the elderly have a more positive perception of whole grains, and modifications in bread and pasta products are better received than are modifications in biscuits. Finally, the pleasure in consumption, the perceived health benefits and health-based motivations are the main criteria that appear to affect the acceptability of whole-grain-rich products (Saulnier and Micard, 2012). In an exploratory study of whole-grain perception, the participants were generally aware of the term ‘whole grain’, but many key barriers to whole-grain consumption were still evident. Nevertheless, in addition to educational efforts, the agro-food industry has quite a few possibilities “to develop novel, but affordable, food products that are able to deliver whole grains in a wide variety of forms, including whole grains ‘in disguise’ for those who are most resistant to change” (page 743) (MacAulay et al., 2013).

Thus, it is interesting to note that in Denmark, whole-grain consumption increased 72% between 2011 and 2013 (The Whole Grains Council, 2013). The Danes were already consuming 32 g of whole grains a day in mid-2011, and now they are ingesting up to 55 g a day on average. The Danes attribute this large increase to manufacturers providing better products and the presence of a packaging symbol that identifies those products. The study indicated that Danes do not eat more bread and grain products than they did previously, but that the increase is because foods like coarse wheat bread and pasta contain more whole grains at present. Furthermore, it has become easier to choose whole-grain products.

Beyond the sensory perception of less refined grain products is the question of whether the consumption of products of plant origin has tended to increase. The study of Dubuisson et al. indicated that an evolution in the consumption of cereals by the French population occurred between 1998–1999 (INCA1 study) and 2006–2007 (INCA2 study); in men and women in the 18–34, 35–54 and 55–79 year age groups, a reduction in the consumption of breads and bread-derived products from 6 to 21% was observed (depending on sex and age), with pasta consumption changing from −10% (women aged 35–54) to +25%, rice and wheat consumption changing from −6 (women aged 18–34) to +44%; and breakfast cereal consumption increasing from +9 to +57%; and pizza and pastry consumption changing from −8 (women aged 35–54) to +33% (Dubuisson et al., 2009). Otherwise, the overall consumption of starchy foods remained constant, with traditional starchy foods, such as bread and potatoes, partially replaced by pasta, rice and wheat (Dubuisson et al., 2009). The stability in the rate of consumption of fish and cereal-based foods, the increased consumption of fruit and vegetables and the decreased consumption of meat, dairy products and sugary foods in France is similar to the trends in the Nordic countries (Dubuisson et al., 2009). There was therefore a tendency toward the increased consumption of grain products (including breakfast cereals), fruits and vegetables and the decreased consumption of products of animal origin, including meat, milk, eggs and cheese (Dubuisson et al., 2009). If this trend of increased consumption of grain products continues as it has since 2007, the development of a more varied range of whole-grain products may accompany it.

Finally, although it is difficult to obtain accurate statistics on the percentage of vegetarians and vegans in France, the change in this population over 10 years indicates the evolution toward the increased consumption of more or less plant-based products. The total number of vegetarians is estimated to be approximately 2% in France (compared with 40% in India). In the issue of 24 May 2012, the French magazine Terra Eco noted “The number of members of the French Vegetarian Association has doubled in three years” (http://www.terraeco.net/). There is very little data available regarding the vegan population.

2.4. Genetic and environmental factors

Plant breeding projects have been conducted within the framework of European research programs to study the genetic and agronomic variability related to the components of the germ, the aleurone layer and other peripheral portions of grains (Andersson et al., 2010; Fernandez-Orozco et al., 2010; Kariluoto et al., 2010; Lampi et al., 2010; Nurmi et al., 2010a, 2010b; Oury et al., 2006; Poutanen et al., 2010; Shewry et al., 2012, 2010a, 2010b). The levels of certain wheat micronutrients, particularly minerals, depend on the genetic origin (magnesium), the agronomic conditions (zinc) and often, interaction between these factors (iron) (Oury et al., 2006). However, programs for the fortification of wheat with iron and zinc exist at the international level (CIMMYT) to overcome the nutritional deficiencies in some of the developing countries. It was also shown that the fibre content and fibre composition (insoluble/soluble ratio) depend on the genetic and agro-environmental conditions (Shewry et al., 2010a; Abecassis and Rousset, 2012). However, the content of soluble fibre (mainly arabinogalactans in wheat) is a highly heritable character (Charmet et al., 2012), i.e., it can be improved by genetic means. However, if this improvement were accompanied by a reduction in the yield or the baking properties of traditional bread, the high-fibre varieties of bread would only be valued in niche markets, which would not attract private breeding companies. In the case of other micronutrients, particularly vitamins and antioxidants, some have a range of heritability (Shewry et al., 2010a,b) and the difficulty for the breeder lies in the expectations of nutritionists: indeed, selecting a particular nutrient may have no meaning in preventive nutrition because it is the totality of bioactive compounds (“cocktail”) that is health-protective via synergistic activities (Fardet, 2010). It therefore seems better to seek grain varieties with a good balance of numerous protective compounds and to promote genetic diversity – a guarantor of this balance – rather than selecting varieties with only a few beneficial compounds. First, it will be interesting to determine a posteriori if intensive selection for yield caused a corresponding decrease in the overall micronutrient content, which appears to occur due to the ‘dilution’ effect (following a better ability of the grain to accumulate grain starch) (Shewry et al., 2011).

2.5. Transformation processes

Cereal grains cannot be consumed as such by humans and therefore grain-transformation processes are essential; however, these processes can either improve or reduce the nutritional quality of cereal products, depending on their intensity and nature. For example, pasta formatting renders starch slowly digestible (Fardet et al., 1998), which is very beneficial for health, whereas drastic extrusion processes burst the initial structure of grains and produce highly gelatinised starch that is rapidly digestible, as is the case for some types of breakfast cereals made for children (Foster-Powell and Miller, 1995).
The nutritional value of cereal products may be increased either through using flours that have been extracted less (i.e., more or less whole-grain flours) or by re-incorporating cereal fractions with a high nutritional density, such as aleurone-layer-rich fractions. For example, research to improve the dry-fractionation processes for grain has led to proposals of ways to improve the composition of flours through increasing their content of constituents from the aleurone layer (Hemery et al., 2007; Delcour et al., 2012). However, the question of the relative energy costs and sustainability arises when comparing dry-fractionation processes to isolate aleurone-rich fractions vs classical milling processes to directly obtain flours of a lower extraction level; we are currently unable to answer this question, which probably depends on the amount of wheat flour produced. In contrast, concerning the second grain- transformation processes, it has been shown that the energy use and greenhouse-gas effects of the bread production chain are mainly determined by baking (i.e., the baking oven) and farming, whereas milling, transport and dough making/fermentation play a minor role (Braschkat et al., 2003).

In addition to optimising the hydro-thermo-mechanical parameters when producing cereal products, we must also consider growing interest in pre-germination or pre-fermentation of grains to optimise their nutrient density (Nelson et al., 2013). Indeed, pre-fermentation may increase the density of bioactive compounds that are beneficial for health (Buddrick et al., 2014; Dordevic et al., 2010; Katina and Poutanen, 2013; Lioger et al., 2006; Poutanen et al., 2009) whereas excessive refining strongly decreases this content (Fardet, 2010). Germination processes can also significantly increase the nutritional and bioactive content of cereals and improve their palatability. Indeed, Nelson et al. stated that “germination techniques may offer a practical, natural, dietary intervention to increase the health benefits and acceptability of whole grains, with potentially widespread effects across populations in attenuating adverse lifestyle disease outcomes” (Nelson et al., 2013). However, the in vitro results now must be substantiated in humans to facilitate the future development of germinated grains (Nelson et al., 2013).

2.6. Legumes as additional ingredients in cereal products

Legumes have long been a traditional staple food. Neverthe- less, legume consumption in France has decreased so that in 2006–2007 the average intake was only 9.7 g/day with a consumption rate of 29.7% (ANSES-Afssa, 2009); which represents an insigniﬁcant decrease of –2.4% compared with the rate observed in the INCA1 1998–1999 study (Dubuisson et al., 2009). However, a resurgence in the consumption of legumes has occurred due to their supplementation of the protein fraction of cereals and the recommendations to increase ﬁbre intake. Whereas combining cereals and legumes has long been practised in developing countries, this combination is less prevalent in the industrialised countries. Some recent work highlighted the importance of such a combination, such as in the case of pasta (Petitot et al., 2010; Petitot and Micard, 2010). The margin for increasing the consumption of legumes – which have a very signiﬁcant nutritional value – is large in France, and this could be accomplished via cereal-product technology (including bread and pasta, which constitute good vectors of pulses) to provide all of the amino acids essential for humans, particularly if the tendency to eat more plant products is conﬁrmed in the coming years. A great deal remains to be done in this area to develop new food products.

3. Proposed topics for future research

From a general point of view, an important question is whether we can develop – from a reverse engineering perspective – a cereal sector that is more respectful of the health potential of cereals and their derivatives.

3.1. Locks and levers

There are locks at different stages of the grain-product chain (Fig. 1). At the agronomic level, the pesticide contamination of the outer layers of grain that results from conventional agricultural practice limits the use of whole grains for nutritional purposes (Hemery et al., 2007). Will the expansion of the least restrictive type of organic culture provide a long-term solution to this problem? Is the diversification of cereal species and/or the introduction of new species (i.e., ancient cereal species and/or cereal species that are consumed in developing countries) economically viable for farmers? There is also the difﬁculty of deﬁning genetic targets (i.e., compounds with a clear metabolic precursor/pathway) and the economic viability of a breeding sector, because improved nutritional value must be deﬁned in collaboration with nutritionists, the relative slowness of which may at ﬁrst seem unattractive to industrialists who too often have a vision of short-term proﬁts or of new-product development based on scientiﬁc ﬁndings that are mostly focussed on only one protective compound, e.g., enrichment with exogenous ﬁbre or resistant starch, when a cocktail of compounds may be health-protective. During the primary transformation stages, can we more systematically produce less-refined ﬂours with lower energy costs? How can we optimise the conser- vation of the germ fraction either without isolating it from the grain or after extraction? Can the techniques for isolating the aleurone layer of wheat be generalised? What are their energy costs? Regarding the secondary transformation stages, how can less- refined grain products that contain less salt, sugar and fat be pro- duced? Downstream of the cereal production sector, are consumers prepared to move toward increasing their intake of less reﬁned and less sugary, salty and fatty cereals?

Globally, it is now recognised that more efforts should be made to retain the phytochemical components initially present in whole-grains throughout the cereals sector. Thus, we must use several levers in the sector, including the agricultural conditions, the choice of grain varieties, more or less thorough reﬁning and less destructive technological processes.

The levers for improving the nutritional properties of cereal products are found at the same levels as the locks in the various stages of the production chain. At the agronomic level, farming practices and plant breeding can be improved; at the genetic level, with the advent of genomic selection, one can consider nutritional criteria in the overall index, as has been realised in the selection of dairy cattle (e.g., fatty-acid contents of milk); at the level of the primary transformation, less flour reﬁning and the preservation of the germ and aleurone fractions may be relevant levers to act upon; at the level of the secondary transformation, the use of less drastic processing technologies (minimal processing, e.g., pre- fermentation and a muesli-type process) and the formulation of less reﬁned products with lower salt, sugar and fat contents appear to be promising sustainable levers; downstream, consumers can be encouraged to evolve toward accepting less-reﬁned grain products with less salt, sugar and fat.

Before looking for levers to improve the health potential of grain products in the framework of a sustainable diet, the advantage to humans of consuming more or less whole-grain products over the long term and understanding protective mechanisms of whole-grains should be demonstrated; for example, the antioxidant
potential of whole-grain cereals compared to refined grain cereals has never been convincingly demonstrated in humans although researchers continue to measure the in vitro antioxidant capacities of cereals and to propose these capacities as essential nutritional properties of whole-grain cereals (Fardet et al., 2008).

3.2. Whole-grain cereals and health

The scientific literature has convincingly shown the lower prevalence of various chronic diseases (type 2 diabetes, cardiovascular diseases and certain digestive cancers) among regular consumers (or among the highest vs lowest consumers) of whole-grain products (Fardet, 2010; Fardet and Boirie, 2014).

However, careful examination of recent reviews on the health potential of cereal products shows that more studies are needed to provide solid arguments for conducting the necessary upstream investigations (e.g., into breeding, the growing conditions, refining, and technologies) using a reverse-engineering approach. We can distinguish, in descending order, the following priorities:

1) There is a lack of intervention studies (RCTs or randomised controlled trials) in humans over the long term to determine causality regarding the protective effect of whole grains; the previously conducted intervention studies did not always confirm the results of observational studies, e.g., an improved antioxidant status after regularly consuming whole grains should be promptly investigated in humans.

2) Observational studies should be carried out, e.g., the association between the consumption of whole-grain products and the prevalence of obesity should be further studied (Fardet and Boirie, 2014) and the association between a high intake of refined grains (± enriched in sugar, salt and fat) (e.g., bread and white rice or children’s breakfast cereals) and the prevalence of chronic disease has not been sufficiently explored (Fardet and Boirie, 2014). Additionally, some recent studies and reviews showed that the association between the consumption of whole-grain products and the quality of bone and mental health should be more clearly determined (Fardet, 2010; Fardet and Boirie, 2014).

3) As to research strategies for investigating the deleterious potential of gluten, we must distinguish between allergenicity, intolerance (celiac disease) and non-celiac gluten sensitivity to gluten; development of cereal products for people who are allergic, sensitive or intolerant to gluten is a good example of research that can be conducted throughout the cereal sector; genetic and technological levers in this area may exist.

4) The contribution of the fibre fraction to the health effects of whole grain has not been resolved; thus, should the health potential of whole grain products be attributed to only their fibre fraction? According to Smith and Tucker, “the relative benefits of fibre extracts compared to fibres directly from whole grain products is a critical area in which additional research is needed” (page 118) (Smith and Tucker, 2011). In addition, recent studies clearly showed that the health potential of grain products cannot be attributed to merely the presence of fibre (Fardet, 2010; Poutanen, 2012). Indeed, many polyphenols (e.g., ferulic and para-coumaric acids) are chemically bound with fibre and are lost during the extraction of the fibre fraction, i.e., they are ‘fibre co-passengers’ (Jones, 2010; Laerke and Knudsen, 2011; Vitaglione et al., 2008) that could be progressively released throughout the digestive tract and provide digestive, cardiovascular and colonic protection (Vitaglione et al., 2008) and positively affect the colonic bacterial population (e.g., beta-glucans and arabinoxylans) (Mitsou et al., 2010; Broekaert et al., 2011), which remains a ‘black box’ that requires further studies.
However, although the health potential of whole-grain products cannot be reduced to that of the fibre fraction (Fardet, 2010; Cho et al., 2013), whole-grain cereals are good sources of fibre for humans and the recommended levels of dietary fibre consumption in France are 25–35 g/day for adults. Considering that approximately 1/3 of fibre should come from cereal-based foods, i.e., 10 g/day, based on the French nutritional database ANSES-Cijual for fibre contents (ANSES-Afssa, 2008), one should consume = 300 g/day of whole-grain cereal-based foods to reach the recommended target of 30 g of fibre/day. In France, adults consume an average of 183 g/day of breads and grain-derived products, such as pasta, breakfast cereals, rice, durum wheat and other cereals, often in refined form (ANSES-Afssa, 2009). This finding suggests that perhaps products should be engineered with more fibre than is present in whole-grain wheat products. However, a more sustainable solution for French people would be to consume more fibre-rich leguminous and oleaginous seeds; currently, the rate of consumption of such seed is less than 10 g/day (ANSES-Afssa, 2009). Therefore, there is a great need for studies on combining cereals with legumes in commonly consumed cereal vectors, such as pasta, breads, breakfast cereals, and biscuits.

5) Another important issue is reducing the sugar, fat and salt contents of cereal-based foods: for example, according to the French PNNS (Programme National Nutrition Santé), the target salt intake should be 8 g/day for adult men and 6.5 g/day for children and adult women (Ministère du Travail, de l’Emploi et de la Santé, 2011). Today, the average salt content of a French baguette is greater than 1.5% and may even reach 2%, and bread products remain the main source of salt. Reducing the intake of salt is expected to reduce the risk of hypertension and cardiovascular diseases.

6) Deregulation of the antioxidant status is the precursor to several hundred diseases in humans. Grains are a very significant potential source of antioxidants, notably phenolic acids; however, few human studies have been conducted to demonstrate their protective antioxidant effects. Moreover, it appears that we should distinguish between the slowly vs rapidly released phenolic acid fractions (Fardet, 2010); the phenolic acids that are rapidly released and absorbed have antioxidant activity and cell-signalling activities, and the phenolic acids that are gradually released in the digestive tract potentially provide antioxidant protection to the mucous membranes (e.g., protection against digestive cancers). Much remains to be demonstrated in this area, including the antioxidant protection of the human colon.

7) Cereals are also a significant source of choline and betaine, two methyl donors that can reduce the level of hepatic triglycerides via the homocysteine cycle, i.e., lipotropes (Fardet and Chardigny, 2013; Fardet, 2010); the bran fraction can contain up to 0.9% betaine and 0.2% choline, yielding a total of 1% by weight of lipotropes. The health impact of these two components of whole grains has never been studied in humans, except for one intervention study conducted in healthy humans that showed an increase in the plasma betaine content after the consumption of aleurone-rich grain products (Price et al., 2010).

Moreover, we know little about the fate of the myo-inositol fraction of phytic acid in humans, and myo-inositol is an important lipotrope. Thus, whole-grain wheat is potentially rich in lipotropes (choline, betaine and myo-inositol) and in micro-nutrients with indirect lipotropic activity, such as some of the B vitamins, magnesium and many polyphenols) (Fardet and Chardigny, 2013). The prevalence of hepatic steatosis in regular consumers of whole-grain products should be studied and the findings confirmed in intervention studies. Indeed, one recent case–control study showed that whole-grain consumption favourably affected the clinical characteristics of patients with non-alcoholic fatty liver disease (NAFLD) and tended to be associated with a less severe disease (OR = 0.97, 95% CI 0.94–1.00) (Georgoulis et al., 2014). Thus, considering that there are several million people who are affected by fatty liver disease worldwide and that this condition can lead to much more severe liver disease (Fardet and Chardigny, 2013), the pool of lipotropes may also have an anticanicogenic potential (Norhaizan et al., 2011; Saad et al., 2013; Shamsuddin, 2002).

The antioxidant and lipotropic potentials of whole grains should therefore be more widely studied in humans, knowing the importance of antioxidant and lipotropic status deregulations in the onset of many chronic diseases.

8) Scientific evidence suggests that a profile of compounds with complementary mechanisms of action rather than a single nutrient is protective (Fardet, 2010). So, rather focussing on studying the relationship between a component and a metabolic effect (the reductionist approach), high throughput technologies of integrative biology should be used to study the nutritional impact of cereals as foods/complex matrices on metabolism as a whole (Fardet et al., 2007) or on gene expression (the holistic approach) to ultimately determine the positive metabolic and gene networks that are activated by the consumption of whole-grain products (Fardet, 2010).

3.3. Refining and new technological processes

The main issues in grain refining appear to be the following: 1) to determine how to maintain the protective compounds of whole grains that are contained mainly in the germ and bran fractions while avoiding the contaminants in the outermost layers of the grain; 2) to reduce the levels of sugars, salts and fats; and 3) to develop new cereal products that are accepted by the consumer.

A review of the literature suggests several questions to be addressed in research, as follows:

3.3.1. First transformation

Can we preserve the germ fraction in flour without prior isolation, stabilisation and reincorporation? Regarding the contamination of the outer layers of the grain, is this currently a real risk to health? Further studies should be conducted to definitively answer this question. Regarding the aleurone layer, there are now well-developed techniques for isolating it or maintaining it during fractionation (while excluding the outermost layers, such as the pericarp) (Barron et al., 2012), but can these be widely applied and are they sustainable in the long term in terms of their energy cost?

In addition to offering complete or semi-complete flours, these issues can be addressed by acting on the ‘formulation’ lever, i.e., how flour is refined and whether fibre and/or the previously isolated aleurone layer are added, with the risk, however, of losing some of the ‘physical structure effects’ of whole grain.

3.3.2. Second transformation

At the level of the second transformation, several issues should also be addressed. Firstly, the use of softer technologies for shaping grain products should be further studied (“minimal processing”). The literature suggested the following areas of research: the effects of cereal pre-fermentation/germination on the nutrient density of cereal products and reconsidering the hydro-thermo-mechanical
parameters used during extrusion to reduce the gelatinisation of starch and preserve the physical structure of the food matrix, perhaps drawing on muesli-production techniques. Preserving the physical structure of the matrix has many potential health benefits, such as a more gradual release of nutrients, increased satiety, a positive effect on passage through the intestine and a positive effect on the intestinal flora (Wang et al., 2014).

Secondly, multiple grain species can be mixed to maximise the intake of bioactive compounds.

Third, is it feasible to decrease the levels of salt, sugar and fat from a technological point of view, and will products with lower levels be accepted by the consumers? A suggestion is to replace the salt (or sodium chloride) with a mixture that includes NaCl and calcium carbonate, potassium and magnesium salts and various trace elements (Rémesy et al., 2014). These saline mixtures, like those in animal feed, could be easily incorporated in bread to give it the status of a particularly balanced food. Research on lowering the contents of sugar and salt while maintaining the consumer’s acceptance, e.g., in biscuits (Villemjean et al., 2012), are in progress.

3.4. Genetic selection and agronomic conditions

Upstream, at the agronomic and genetic levels, several issues also need to be addressed. It seems promising to attempt the following:

1) To encourage the diversity of wheat varieties or cereal species (ancient and/or pseudo-cereal grains) to benefit from the greatest possible diversity of microconstituents and bioactive compounds rather than to focus on a single grain component. Is the introduction of new varieties and/or species (sorghum, quinoa, millet and others) economically and agronomically viable?

2) To screen varieties to seek those that have the best balance of the largest number of bioactive compounds (e.g., via metabolomics (Shewry et al., 2013). For example, regarding antioxidants, focussing on only one antioxidant has little meaning because more than 30 compounds in whole grains have antioxidant activities: their synergistic action may be effective, not the action of a single compound (Fardet, 2010; Thompson et al., 2006). This concept holds true for all of the other compounds with a given physiological effect, such as lipotropes, lipid-lowering compounds, anti-carcinogens, and anti-inflammatory compounds. Thus, rather than focussing on improving the content of a single component, genetic-selection research could focus on ‘packages’ of compounds, such as antioxidants, lipotropes or anti-inflammatory compounds, to develop varieties with high antioxidant or lipotropic potential,

3) To measure the impact of organic agriculture on the health potential of grain products via a prospective cohort study (organic vs conventional cereal products), even though this type of study is very difficult and expensive to conduct. Notably, however, the products of organic agriculture do not appear to have a better nutritional composition than those produced using conventional agriculture, as was generally shown for crops (Dangour et al., 2009, 2010) or more specifically, for maize (Röhlig and Engel, 2010) or wheat (Nitika et al., 2008) using the identical grinding mode (Chaurand et al., 2006), although the level of antioxidants and some mineral compounds might be generally higher in some plant products (Lairon, 2010). However, in vitro measurements of the levels of nutrients cannot alone predict their nutritional effects in humans. Nevertheless, the robustly demonstrated added value of organically grown crops is currently fostering a greater respect for the environment.

4) To study the impact of reducing the rate of nitrogen fertilisation. The most significant environmental effect of the implementation of the Nitrate Directive, which was issued in 1995, is its major contribution to decreasing the N balance (N surplus) in soil, particularly in Denmark, Ireland, the Netherlands and the United Kingdom (van Grinsven et al., 2012).

3.5. The more general issue of plant vs animal proteins

In the framework of a sustainable diet, the question of eating more plant than animal products is increasingly emphasised. Nutritionists agree that we should consume a maximum of 20% animal products and a minimum of 80% plant products; based on the INCA2 survey, the respective proportions are estimated to be approximately 35–40 and 60–65% in the French population (ANSES-Afssa, 2009). In addition, the Agrimonde report (conducted jointly by INRA and CIRAD) estimated that by 2050, to ensure environmental sustainability, 15% of the energy intake should be from animal products and 85% from plant products (Agrimonde, 2009).

However, encouraging the ingestion of more plant products and therefore more vegetable proteins requires assessing the long-term effects of the increased consumption of plant-based proteins and thinking about what animal/plant protein ratios to achieve, with upstream implications on crop-cultivation patterns (e.g., reducing the input and the carbon cost (Jeuffroy and Oury, 2012)). Cereal products could play a key role in this development, particularly in combination with legumes, for which they are good vectors, e.g., biscuits, breakfast cereals, pasta and bread are among the most consumed cereal products.

However, the distinction between plant and animal proteins appears to be rather reductionist for several reasons, as follows: 1) we know we can compare the value of meat protein with that of a combination of cereals with legumes even though the average total digestibility of the latter is a little worse; 2) the environment of the protein and the protein-associated components matter, as well as does the structure of the food matrices. Therefore, the issue is much more complex than whether proteins are derived from animal- vs plant-based products. I believe the real issue is more holistic, i.e., to move towards more complex plant-based foods.

4. Conclusions and perspectives

Improving the health potential of cereal products requires a reverse engineering-based approach. The health potential of cereal products and consumer’s acceptance should be prioritised before all other considerations.

However, there are numerous outstanding issues about the health potential of cereal-based foods that remain to be investigated. First, the relationship between cause and effect has not been sufficiently well established to reinforce the conclusions of epidemiological studies. Second, researchers must more precisely characterise whole grains and their bioactive compounds and determine how these factors interact to affect the metabolic and physiological functions far beyond those of the gut. Third, more studies are needed to confirm the role played by whole grains in the protection against colorectal cancer via their fibre content. Fourth, the polyphenols associated with the fibre fraction (‘fibre co-passengers’) in whole grains may play a positive role in the oxidative and inflammation processes underlying obesity and this issue must be addressed. Fifth, a consensus on the definition of whole-grain cereals is a necessary pre-requisite for a common language in
basic research and clinical and intervention studies of cereals, as well as in the field of controlled labelling. The standardisation of this definition and related labelling and health claims will help to minimise the confusion of the consumer and facilitate advocating for a healthy diet that includes whole grains (Gibson et al., 2013).

More generally, it is clear that the agro-food industry and cereal sector must adapt to the production of grain products that are more ‘friendly’ for the environment and for health (eco-conception) at an economically viable price. This goal can be realised only if there is a concerted and integrated approach among all of the actors in the sector.

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