Trends in Food Science & Technology 107 (2021) 114–123

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Biochemical characteristics and potential applications of ancient cereals - An underexploited opportunity for sustainable production and consumption

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ARTICLE INFO

Keywords:
Ancient grains
Ancient wheat
Consumer preferences
Nutritional properties
Sensory profiles
Wholegrain

ABSTRACT

Background: There is currently renewed interest in foods based on ancient cereals because consumers often consider such foods to be healthy and sustainable. Interest in ancient cereals is also growing among farmers and in the food industry due to increased demands for adaptability and the urgent need to preserve genetic diversity.

Scope and approach: In this review, we attempt to summarise recent findings regarding the content of nutrients and bioactive compounds in ancient cereals and their potential impact on human health in comparison with modern varieties. A literature review was conducted by collecting, evaluating and analysing data from publications in peer-reviewed scientific journals written in English language.

Key findings and conclusions: As indicated in several studies, ancient cereal varieties might have beneficial nutritional profile and consumers appreciate the taste and flavour of foods based on ancient cereals. These cereals have the potential to contribute to the improved sustainability and resilience of cropping systems. In addition, the production and consumption of foods based on ancient cereals indirectly encourages biodiversity, which has become a priority in environmental and organic farming circles. In conclusion, due to their unique nutritional value and phytochemical profile as well as their sensory characteristics, there is good potential for ancient cereals and associated products to become a part of a healthy diet.

1. Introduction

Cereal-based food products constitute a major part of the daily human diet. Throughout history they have been, and still are, an important source of protein, dietary fibre, and bioactive compounds with antioxidant and anti-inflammatory effects. The major cereals include wheat, rye, rice, barley, oats, corn, millet and sorghum. Among these, wheat, maize, and rice dominate world agricultural production. Cereal-based bread and porridge-like foods were already an important part of the human diet in prehistoric times (Valamoti et al., 2019). There is strong evidence that prehistoric man was able to prepare gruel from grains and water. Nowadays, we are experiencing a resurgence of interest in foods based on ancient cereals because consumers often consider such foods to be healthy and sustainable (Dinu et al., 2018). According to Giambanelli et al. (2013), ancient cereals are defined as "forms which are represented by populations not subjected to any modern breeding or selection, and sometimes retaining characteristics of wild ancestors, such as individual variability, height, brittle rachis, low harvest index and, in some taxa, hulled kernels". The importance of genetic resources from ancient cereals has been highlighted by several authors as they are able to adapt to the changing environmental conditions resulting from global climate change (Kotschi, 2006; Longin & Würschum, 2016; Moudrý et al., 2011). A promising potential for emmer, einkorn, and rivet wheat to contribute to the improved sustainability and resilience of cropping systems was recently suggested (Costanzo et al., 2019). This suggestion was based on recognition of the field (cover, disease resistance, yield) and the nutritional qualities (protein, lipids, fibre, phenolic compounds) of these species when grown

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https://doi.org/10.1016/j.tifs.2020.12.006
Received 15 March 2020; Received in revised form 14 November 2020; Accepted 6 December 2020

organically in the United Kingdom. However, relatively little is known about the nutritional value and health effects of ancient cereals. The potential health benefits of the consumption of ancient cereal-based products need to be evaluated and consumers need to be made more aware of them. Thus, more research is urgently needed to provide new approaches to the creation of ancient cereal-based products, evaluate their health effects and elucidate the mechanisms behind these effects.

Bread wheat (*Triticum aestivum* L.) was domesticated in southeast Turkey approximately 9000 years ago (Feldman & Millet, 2001). The most common ancient wheat species include emmer *(Triticum dicoccum*), einkorn (*Triticum monococcum*), khorasan (*Triticum turgidum* ssp. *turanicum*) and spelt (*Triticum spelta*). Despite the increased interest in ancient species, their use in bread-baking has been limited until recently.

Besides bread-baking, there are also endless possibilities for using ancient cereals in both traditional and new foods. For example, einkorn flour may be used as a material for manufacturing new foods with high nutritional quality, such as crackers and snacks (Hidalgo and Brandolini, 2017; Hidalgo et al., 2010, 2016; Messia et al., 2012). Ranucci et al. (2018) introduced emmer as an ingredient in frankfurters using a recipe derived from an ancient Roman cookbook. However, it has to be remembered that any additional information provided can only increase their popularity if consumers are satisfied with the taste experience of the product. Additionally, millets might be an attractive of healthy diet due to their sensory characteristics and nutritional quality (Brasil et al., 2015; Kumar et al., 2018).

The development of nutritious, safe, affordable and sustainable food products that can prevent lifestyle-related non-communicable diseases is highly desirable. In recent years, dietary fibre has become an attractive ingredient for consumers because of the role of fibre in reducing the risk of several non-communicable diseases (Slavin, 2004). The greater health benefits of wholegrains compared to refined grains are well known (Ye et al., 2012). In adults, the recommended intake of dietary fibre ranges from 25 to 38 g/day (EFSA, 2010; NNR, 2012). However, the intake of dietary fibre in many EU countries is currently lower than recommended in all age groups including children (Becker et al., 2016; Hoppu et al., 2010; Osowski et al., 2015). Foods from whole ancient grains have, therefore, considerable potential to be introduced to consumers as a part of a healthy diet due to their unique nutritional value, phytochemical profile and sensory properties.

In addition, cultivation of older species does not always require the intense use of mineral fertilizers, which makes them more suitable for organic farming where organic fertilizers may be applied (Gomez-Becerra et al., 2010; Rüegger & Winzeler, 1993). The increasing awareness of climate change is another reason for the renewed interest in ancient grains, since they have shown more resilience to drought or other extreme weather conditions than modern varieties (Slama et al., 2018; Cheng, 2018). It is also important to maintain a divergent pool of wheat genotypes that can be grown under various environmental conditions as well as different wheat varieties as genetic stock for further improvements. For example, the beneficial modifications of miRNA-regulated pathways can be a promising tool for crop improvement (Alptekin & Budak, 2017). Einkorn genetic resources diversity exploration was recently reviewed by Zaharieva and Monneveux (2014). Genetic divergence in wild emmer wheat and spelt have also been studied (Bertin et al., 2001; Hussain et al., 2012; Ren et al., 2013).

In the present review we attempt to throw light on the association between the biochemical composition of foods based on ancient cereals and their health-promoting properties and sensory characteristics as well as consumer attitudes and acceptance.

2. Nutritional composition of modern and ancient cereals

In general, cereals are a good source of protein, vitamins and minerals, dietary fibre and valuable bioactive compounds (Shewry & Hey, 2015a). There are a large number of publications concerning the grain composition of modern wheat (Shewry & Hey, 2015a). In contrast, ancient cereals have only recently gained worldwide recognition for their nutritional properties, in particular their high protein content.

2.1. Protein composition

Although cereal proteins are considered to be of lower quality than proteins from animal products due to their suboptimal amino acid profile and lower protein digestibility (Joye, 2019), cereal proteins should be part of a healthy balanced diet. It is well known that the protein content of cereals is mainly determined by genetic and environmental factors (Chope et al., 2014; Geisslitz et al., 2019). Thus, it is not surprising that modern and ancient species display genetically related differences in nutritional composition. Various studies have shown that common wheat has a lower protein content compared to ancient species (Table 1). In most industrialized countries, the recommended daily protein intake is easy achievable and, in terms of health, the quality of dietary protein is more important than just the protein content.

Protein quality is determined by the quantities and proportions of essential amino acids; these cannot be synthesized by the human body and must therefore be obtained from the diet. Akar et al. (2019) demonstrated higher concentrations of essential amino acids (especially threonine, lysine, valine, methionine, leucine, isoleucine and phenylalanine) in einkorn compared to emmer and durum wheat. In contrast, Abdel-Aal and Hucl (2002) observed that einkorn and einkorn products were relatively low in lysine and high in glutamic acid compared to other wheat products. *In vitro* protein digestibility did not differ between einkorn, spelt, Khorasan and modern wheats (Abdel-Aal & Hucl, 2002).

Cereal grains contain both water-soluble and water-insoluble proteins. Water-insoluble proteins include the proteins glutenin and gliadin, which are components of gluten and have a storage function. In bread making, gluten is responsible for the elasticity of dough, which in turn determines the chewiness of bread. Gluten proteins are usually present in higher quantities in ancient species compared to modern species, although the gluten composition might differ between modern and ancient cultivars (De Santis et al., 2017). Geisslitz et al. (2019) recently carried out impressive work comparing the gluten protein composition of ancient and modern wheat species. Overall, gluten and gliadin contents were comparable or higher in the ancient species einkorn, emmer and spelt than in modern wheat (Table 1). Similarly, the seeds of the ancient types of tetraploid wheat Graziella Ra and Kamut® khorasan contain higher concentrations of gliadin compared to modern wheat (Colomba & Gregorini, 2012). The ratio between gliadin and glutenin was higher in ancient wheats compared to modern species due to common wheat having a higher glutenin content (De Santis et al., 2017; Geisslitz et al. 2018, 2019). In contrast, two ancient durum wheat cultivars, Senatore Cappelli and Saragolla in Italy, contained higher levels of both glutenin and gliadin (gamma-gliadin) compared to the commercial variety Svevo (Rocco et al., 2019). Glutenin is mainly responsible for the elastic properties of dough. The ratio between gliadin and glutenin affect the dough rheological properties, with higher glutenin content, imparting improved technological performance in the modern varieties (Barak et al., 2014). Protein content of millets is generally comparable to wheat, although high variations between the varieties were observed. Thus, finger millet, the most important small millet in the tropical countries including Sri Lanka, have lower protein contents than pearl millet (8.5% vs 13.4%) (Jayawardana et al., 2019; Saleh et al., 2013). Millets are gluten-free and can be used in designing the modern foods for gluten-sensitive population (Kumar et al., 2018). Additionally, pearl millet and finger millet have higher content of some essential amino acids (leucine, isoleucine and lysine) than wheat (Anitha et al., 2019; Dias-Martins et al., 2018).

Table 1
Protein composition of modern and ancient grains.

Species	Total protein (%)	Gluten (mg/g)	Gliadin (mg/g)	Glutenin (mg/g)	Notes	Reference
Common wheat	11.6	28.2	60.1	31.9	Data are presented as mean values. Analyses were performed on refined flour	Frakolaki et al. (2018)
	8.3–12.1	33.2–80.4	22.2–57.5	10.9–25.0	Data are presented as range. Analyses were performed on wholemeal flours	Geisslitz et al. (2019)
Spelt	15.2	18.5	59.8	46.7	Data are presented as mean values. Analyses were performed on whole-grain flour	Frakolaki et al. (2018)
	9.3–16.1	55.7–111.6	45.9–85.5	14.1–25.4	Data are presented as range. Analyses were performed on wholemeal flours	Geisslitz et al. (2019)
	17.4 and 16.5				Mean values for hard and soft spelt, respectively	Abdel-Aal and Hucl (2002)
	14.8				Mean value	Angioloni and Collar (2011)
Einkorn	9.8–14.2	57.1–85.7	50.5–74.8	5.4–16.8	Data are presented as range. Analyses were performed on wholemeal flours	Geisslitz et al. (2019)
	17.9				Mean value	Abdel-Aal and Hucl (2002)
Emmer	8.9–14.2	51.5–101.0	42.2–84.3	5.8–22.7	Data are presented as range. Analyses were performed on wholemeal flours	Geisslitz et al. (2019)
Khorasan	15.4				Mean value	Abdel-Aal and Hucl (2002)
	17.8				Mean value	Angioloni and Collar (2011)
			41.4 ± 0.1		Mean value ± standard deviation	Colomba and Gregorini (2012)

2.2. Carbohydrates – starch and dietary fibre

Starch is an important reserve polysaccharide in cereals. Starch represents a mixture of amylose (linear chain) and amylopectin (branched chain) and an important determinant of the dynamic properties of dough, especially during heating. In particular, gelatinisation of starch during baking affects the final bread quality. Sofi et al. (2013) did not find any differences between total starch content in Kamut® khorasan and modern wheat flours, whereas the amylose/amylopectin ratio was significantly higher in Kamut® khorasan wheat. The amylose content was also generally higher in emmer cultivars compared to durum wheat (Guzmán et al., 2011).

Wheat dietary fibre mainly consists of the non-starch polysaccharides arabinoxylan, arabinogalactan peptide, β-glucan, the resistant oligosaccharide cellulose, and the nonpolysaccharide compound lignin. The most comprehensive comparison of dietary fibre and its components in different cultivars included 151 bread wheat cultivars, 10 durum wheat cultivars, and 5 lines each of einkorn, emmer and spelt (Gebruers et al., 2008). In this work, modern bread wheats were shown to contain higher levels of dietary fibre (11.5–18.3%) compared to einkorn and emmer (7.2–12.8%). The lower content of dietary fibre in ancient wheat cultivars has also been reported in other studies (De Santis et al., 2018; Fares et al., 2019). The composition of the dietary fibre also differed between modern and ancient species. Common wheat bran (dry matter) contained 17% arabinoxylan, whereas durum and spelt wheat bran contained 12%, and einkorn and emmer 9% (Gebruers et al., 2008). Moreover, in the same study, einkorn and emmer wheats contained almost half the β-glucan content compared to other types of wheat. Lignin levels were similar in ancient and modern species (Gebruers et al., 2008).

Millets are also excellent source of dietary fibres with the content comparable with that of wheat (Jayawardana et al., 2019; Thippeswamy et al., 2016).

2.3. Minerals

An adequate intake of minerals is important for human health. There is a high variation in the mineral content of cereals (Table 2). Several authors have shown that modern wheats have low zinc and iron contents (Fan et al., 2008; Chatzav et al., 2010; Erba et al., 2011; Xu et al., 2011; Moreira-Ascarrunz et al., 2016). Ancient cereals contain higher levels of both zinc and iron, as well as other minerals, compared to modern wheat (Table 2) and, if consumed in combination with other plant-based foods, have the potential to provide a substantial contribution to the intake of minerals. Similarly, finger and pearl millets contains high levels of calcium, potassium and iron (Table 2; Anitha et al., 2019; Kumar et al.,

Table 2
Content of some minerals in modern and ancient grains.

Species	Major minerals, g/kg					Minor minerals, mg/kg					
	Ca	P	Mg	K	S	Fe	Mn	Zn	Cu	Se	Reference
Common wheat	0.4	4.2	1.4	5	1.3	38	26	35	4		Suchowilska et al. (2012)
	0.3					27		30			Kohajdová and Karovičová (2008)
		1.8	0.5	1.6		20		15		0.7	Sofi et al. (2013)
Spelt	0.4	4.7	1.5	4.2	1.8	50	27	47	5		Suchowilska et al. (2012)
	0.3					57		47			Kohajdová and Karovičová (2008)
Einkorn	0.4	5.2	1.6	4.3	1.9	49	28	53	4		Suchowilska et al. (2012)
Emmer	0.4	5.1	1.7	4.4	1.9	49	24	54	4		Suchowilska et al. (2012)
Khorasan		2.9	0.9	2.7		24		25		0.9	Sofi et al. (2013)
Finger millet[a]	2.4–3.4	1.6–2.9		3.8–5.2		40–48	51–61	12–17			Nakarani et al. (2021)
	3.6–4.5					26–29		20			Anitha et al. (2019)
Pearl millet	2.2–3.0					47–85		43–55			Anitha et al. (2019)

[a] Data are presented as ranges for ten (Nakarani et al., 2021) or two millet genotypes (Anitha et al., 2019).

2018; Nakarani et al., 2021). It should be noted, however, that cereals contain phytate and certain proteins that interfere with mineral absorption and reduce mineral bioavailability (Baye et al., 2017). To the best of our knowledge, the bioavailability of minerals from modern and ancient species has never been compared. Such comparisons should be included in future studies because a higher content of minerals in a type of grain does not necessarily mean improved uptake or availability.

It should also be noted that cereals and cereal products may contain toxic metals such as cadmium and lead. Comparative assessment studies of cadmium concentrations in modern and ancient species are limited. Suchowilska et al. (2012) did not observe concentrations of cadmium and lead above 0.2 mg/kg, which is the EU maximum permissible level of these metals in cereals and cereal products meant for human consumption (European Commission Regulation (Ec) No 1881/2006).

2.4. *Vitamins and phytochemicals*

Cereals are generally rich in bioactive compounds (secondary metabolites) that are concentrated in the outer layers of the grain. Among the bioactive compounds that originate in plants, phenolic compounds (phenolic acids and flavonoids) have attracted considerable attention because of their health-promoting properties. The results of a study acronymed HEALTHGRAIN (Exploiting Bioactivity of European Cereal Grains for Improved Nutrition and Health Benefits, an Integrated Project of the European Union's Sixth Framework Programme's "Food Quality and Safety" activity) demonstrated that the content of phenolic compounds is generally higher in ancient wheat species (einkorn, emmer, and spelt) than in modern varieties (Andersson et al., 2008; Shewry & Hey, 2015b). Total polyphenol content was also higher in Kamut®-khorasan flour compared to modern wheat (1.7 vs 1.21 mg/g dry matter) (Sofi et al., 2013). Additionally, the same study showed that Kamut® khorasan flour contained a higher concentration of flavonoids (0.34 vs 0.20 mg/g dry matter). The potential bioavailability of phenolic compounds was, however, negatively associated with levels of dietary fibre (Angioloni & Collar, 2011).

Alkylresorcinols are phenolic lipids that are mainly found in rye and wheat brans, with the highest concentrations in the kernel intermediate layer (Landberg et al., 2008). Alkylresorcinols and alkylresorcinol metabolites have been intensively studied for use as biomarkers of wholegrain intake (Wierzbicka et al., 2017). Andersson et al. (2008) analysed the contents of alkylresorcinols in 131 winter wheats, 20 spring wheats, 10 durum wheats, 5 spelt wheats, and 10 early cultivated forms of wheat as a part of the HEALTHGRAIN diversity screen. In that study, an overlap between the contents of alkylresorcinols in modern and ancient wheats was observed (Andersson et al., 2008). Similarly, Ziegler et al. (2016) reported comparable alkylresorcinol contents in whole grain flours of 15 varieties each of bread wheat, spelt, durum, emmer, and einkorn although the contents varied greatly among the varieties of the same species.

Tocols (tocol derivatives, e.g., tocopherols and tocotrienols) have an antioxidant activity and protect mono- and polyunsaturated fatty acids from oxidation. Tocols are concentrated in the pericarp and are also present in the endosperm of cereal grains. Alpha-tocopherol (vitamin E) is probably the best known tocol. Hidalgo et al. (2010) investigated the stability of tocols from einkorn and modern wheats during processing (bread, biscuits, and pasta) and demonstrated that einkorn contributed more tocols to the final products than durum and modern wheats. For example, in pasta, the tocol contents were 20.4 (einkorn) vs. 8.2 (durum) vs. 5.3 (bread wheats) mg/kg dry matter. Several studies have reported higher total tocol content in einkorn compared to other species (Hejtmankova et al., 2010; Lachman et al., 2013). This high total content is likely due to the high levels of tocotrienols in einkorn. Unprocessed einkorn grains were found to contain lower levels of alpha- and beta-tocopherol and higher tocotrienols levels compared to spring wheat and emmer (Lachman et al., 2013). Carotenoid content has also often been found to be higher in ancient species compared to modern wheats (Hidalgo & Brandolini, 2014, 2017; Lachman et al., 2013). For example, einkorn was shown to contain an almost 10-fold higher lutein content than modern wheat (Ziegler et al., 2016). Interestingly, carotenoid degradation in the flours was lower for einkorn than for modern wheat, making einkorn-based products richer in carotenoids (Hidalgo & Brandolini, 2008).

3. Ancient cereals in health and disease

To date, relatively few studies have focused on the impact of the intake of ancient cereals on human health.

3.1. *Gluten-related disorders*

The frequency of gluten-related disorders is gradually increasing and this is gaining the attention of the medical and scientific community (Rubio-Tapia et al., 2009). Coeliac disease is an autoimmune condition that is characterised by the loss of absorptive villi in the small intestine thus preventing nutrients from being properly absorbed. In patients diagnosed with coeliac disease, peptides high in proline, referred to as T-cell epitopes, are not digested and accumulate in the small intestine initiating the immune response associated with coeliac disease. These effects are mainly due to the gliadin fractions of gluten, especially α-gliadin and γ-gliadin (Qiao.et al., 2004; Salentijn et al., 2012). There is no treatment for coeliac disease and the only remedy is to follow a gluten-free diet. It is, therefore, extremely important for people with coeliac disease to choose the right bread for consumption. Recently, consumers have received controversial information about the safety of ancient cereal-based products for people with coeliac disease. It has been suggested that ancient grains might have lower immunogenic properties than modern grains and can therefore be less toxic for those with coeliac disease (Pizzuti et al., 2006). It should, however, be emphasised that Pizzuti et al. (2006) used an *in vitro* distal duodenum culture system to compare the effects of gliadin from modern wheat and einkorn. Since the results from *in vitro* studies cannot be easily translated into more complex *in vivo* situations, it can be concluded that a solid scientific basis for the inclusion of ancient cereals in the diet of people with coeliac disease is lacking. Colomba and Gregorini (2012) identified a series of α-gliadin epitope variants with suggested T-cell stimulatory capacity in ancient wheats (Graziella Ra and Kamut® khorasan). Einkorn is also known to express T-cell stimulatory toxic gliadin epitopes (Van Herpen et al., 2006) and should therefore be avoided by those with coeliac disease.

Though ancient cereals are not safe for persons diagnosed with coeliac disease (Šuligoj et al., 2013; Zanini et al., 2013, 2015), and probably for persons with non-coeliac wheat sensitivity. Non-coeliac wheat sensitivity, also referred to as non-coeliac gluten sensitivity, is a disorder characterised by intestinal symptoms (diarrhoea or constipation, abdominal pain, meteorism, postprandial fullness, etc.) and extraintestinal manifestations (headache, fatigue, depression, muscle pain, dermatitis, anaemia, etc.) in patients without coeliac disease or wheat/gluten allergy. The exact pathogenesis of non-coeliac wheat sensitivity is still not well understood. It was previously believed that gluten is entirely responsible for this disorder, however there is increasing evidence that high amounts of amylase trypsin inhibitors (ATIs) in gluten-containing cereals might lead to gastrointestinal symptoms through the stimulation of toll-like receptors (TLRs) (Junker et al., 2012). The content of ATIs in different wheat species was recently measured in common wheat, durum wheat, spelt, emmer, and einkorn (Geisslitz et al., 2018). The results showed that three einkorn cultivars contained lower concentrations of ATIs compared to other wheats. In contrast, spelt and emmer contained significantly higher ATI concentrations than those of common wheat (Geisslitz et al., 2018), although with lower *in vitro* bioactivity compared to common wheat (Zevallos et al., 2017). This indicates that ancient wheats might produce lower toxicity compared to modern varieties. Further research is, however, needed to evaluate the tolerability of ancient species by persons with non-coeliac wheat sensitivity.

3.2. Management of noncommunicable diseases

The prevalence of noncommunicable diseases (NCD), including cardiovascular diseases, cancers and type 2 diabetes, is currently increasing worldwide. The biggest contributors to the global burden of disease were suggested to be diets low in wholegrains, high in sodium, and low in fruits, nuts, seeds or vegetables (Branca et al., 2019).

There is growing evidence that the consumption of wholegrains reduces the risk of NCD (Priebe et al., 2008; Slavin, 2004). The possible role of ancient cereals in the prevention of noncommunicable diseases has not been extensively studied. To the best of our knowledge, there are only a limited number of quantitative studies summarising the effects of ancient cereal consumption on the markers of noncommunicable diseases.

An animal study on Zucker diabetic fatty rats demonstrated that emmer- and einkorn-based diets resulted in a downregulation of key regulatory genes involved in glucose and lipid metabolism, while spelt and rye resulted in lower glycaemic response compared to modern wheat (Thorup et al., 2014). This was suggested to contribute to a prevention of or delay in the development of type 2 diabetes.

A recent study by Alyami et al. (2019) compared postprandial glucose levels after consumption of breakfast porridges made from ancient varieties of millet grains (pearl millet and finger millet) with those made from oat and rye. The authors showed that the group consuming pearl millet had lower average appetite scores measured using a subjective visual analogue scale (VAS). Moreover, the same group had lower postprandial blood glucose responses as measured by the incremental area under the glucose curve; insulin levels were not measured. This pilot study indicated that including millet porridge as part of breakfast might be an attractive alternative to rye and oats because of its possible prolonged satiating properties. However, the results from this study should be taken with caution because of the small number of participants (n = 7). Additionally, the results in relation to the finger millet were inconclusive because some participants could not finish all the test meal because of the low palatability of the finger millet porridge. VAS scores were also only measured during the 120 min after breakfast; a longer time period is needed to evaluate the effect of a meal on satiety and hunger scores.

In another intervention with 30 healthy individuals, a Kamut® khorasan-based diet consumed for 3 months showed a higher release of short-chain fatty acids (SCFA) and phenol compounds compared to that of a modern durum wheat diet (Saa et al., 2014). Besides having an important role in chronic inflammation and immune responses, SCFA are also associated with reduced appetite and food intake, which is important in obesity and metabolic regulation (glucose and lipid homeostasis) (Dugas et al., 2018). Moreover, in a randomised, single-blinded, cross-over trial on 22 healthy individuals, the consumption of Kamut® khorasan-based products (bread, pasta and crackers) resulted in a significant reduction of metabolic risk factors including total cholesterol, low-density lipoprotein cholesterol and blood glucose (Sofi et al., 2003). Thus, a Kamut® khorasan-based diet might be useful as part of a strategy to prevent diet-induced obesity. In addition, khorasan consumption was shown to reduce total and LDL cholesterol, insulin and glucose in 21 patients diagnosed with type 2 diabetes (Whittaker et al., 2017).

3.3. Oxidative stress and inflammatory parameters

Oxidative stress plays an important role in the development of various human diseases. An impressive body of research underlines the impact of diet on oxidative stress and inflammatory parameters (Tan et al., 2018; Haβ et al., 2019). It has been suggested that ancient cereals consumed as a part of the diet could potentially play a beneficial role in protecting against oxidative stress (Sofi et al., 2018). Positive effects on some oxidative and inflammatory parameters have mainly been described for Kamut® khorasan wheat.

HepG2 cells, a human hepatoma cell line, were used in an *in vitro* model to study the anti-inflammatory and antioxidant properties of wholegrain ancient Kamut® khorasan wheat grown in North America, ancient khorasan wheat grown in Italy, and modern durum wheat (Valli et al., 2016). In vitro digested cookies made from the flour of these grains were incubated with HepG2 cells, and thiobarbituric acid reactive substances (TBARS), reactive oxygen species (ROS), total antioxidant capacity and thiolic content were assessed. Kamut® khorasan flour had the highest protective effect against oxidative stress induced by H_2O_2 exposure as suggested by an increase in TBARS, while ROS concentrations were not affected by type of flour. In the same study, concentrations of the cytokines interleukin-8 and interleukin-10 were also measured; no effects on the cytokines of the type of flour were observed. Interestingly, North American Kamut® khorasan had higher antioxidant activity compared to Italian khorasan flour (Valli et al., 2016), probably due to a higher content of selenium. Based on the results from a cross-over dietary intervention study, Sofi et al. (2013) suggested that a replacement diet using Kamut® khorasan-based products might reduce markers of oxidative stress and inflammatory status. A recent randomised, single-blinded, crossover trial in basketball players confirmed that a khorasan-based diet might reduce the inflammatory status through a reduction of pro-inflammatory monocyte chemotactic protein-1 (MCP-1) concentrations (Spisni et al., 2020). However, the concentrations of cytokine interleukin-8 (IL-8) and interleukin-1 receptor antagonist (IL-1ra) were not seen to be affected by diet; this was probably due to a low number of participants. Earlier, a study on rats also showed that the ancient Kamut® khorasan grain was more effective in reducing oxidative damage and inflammatory status (Benedetti et al., 2012; Gianotti et al., 2011).

In line with the above-mentioned findings, a whole Kamut® khorasan-based diet was found to result in the higher release of SCFA in the human gut in comparison to whole durum wheat (Saa et al., 2014). Similar effects were observed in a pig model after inclusion of einkorn bread in the diet (Barone et al., 2019). SCFA are involved in the regulation of gut homeostasis and play a role in chronic inflammation and immune responses (Bilotta & Cong, 2019).

The potential anti-inflammatory effect of other ancient cereals is largely unknown. The effect of einkorn-based bread on IL-6 and IL-8 production was studied in Caco-2 cells, but the results were inconclusive (Antognoni et al., 2017). A set of several genotypes of oat, rye, spelt, einkorn and other species were investigated for their protective effects against oxidative stress in human HeLa (cervical) and HCT 116 (colorectal) cancer cell lines (Akkoc et al., 2019). Cellular levels of ROS, mitochondrial health, DNA damage and cell survival were analysed as markers of oxidative stress. The extract from modern wheat cultivars was, in general, shown to be less effective against oxidative stress compared to ancient grains (Akkoc et al., 2019).

4. Consumption of ancient cereals

As mentioned above, an adequate consumption of wholegrains provides important health benefits, such as reduced risk of NCD development (Priebe et al., 2008; Reynolds 2019; Slavin, 2004). In many countries, however, consumption of wholegrains is too low (Kyrø et al., 2012). The recommendation in the Nordic countries is 70 g per day for women and 90 g for men (NNR, 2012). A recent survey in Sweden of dietary habits among adults demonstrated that the average consumption of wholegrains was 39 g for women and 46 g for men (Amcoff et al., 2012). To increase the amount of wholegrains and dietary fibre in the diet, Thompson and Brick (2016) recommended an old concept: “consume cereal and pulse crops in combination as dietary staples, in adequate amounts every day”. Saha et al. (2019) concluded that policy makers should initiate necessary actions to modify dietary intake. Both the production and consumption of ancient grains vary considerably between countries but are generally lower than for modern grains (Taylor & Awika, 2017). Well tasting products based on ancient grains are attractive to consumers and could therefore be used to increase the intake of fibre (Jankielsohn & Miles, 2017; Holmer et al., 2012) and might also provide further health benefits (Shewry & Hey, 2015a). However, sensory aspects have to be taken into account when developing products based on ancient cereals.

5. Sensory aspects of ancient cereal products

Although tastiness is the most important factor for consumers, descriptions such as ancient, natural, organic, old variety, heirloom, local or wholegrains are most likely to have a favourable influence on the consumer (Bruschi et al., 2015; Sandvik et al., 2014; Teuber et al., 2016). A variety of health claims may also have a positive impact on consumer liking (Gosine & McSweeney, 2019). It has been suggested, much like the concept of terroir, that heirloom grains are being employed to leverage new values in the marketplace and construct new definitions of deliciousness (Jones, 2017). However, several studies have suggested that older or ancient wheat varieties are characterised by poorer rheological and technological properties compared to modern varieties (Geisslitz et al., 2018; Guarda et al., 2004; Sobczyk et al., 2017).

5.1. Taste, flavour and odour

Differences in the odour and flavour of cooked grains, flour, porridge and bread wheat varieties, made from ancient and modern species, were analysed by both a trained, analytical sensory panel and with gas chromatography (Starr, 2015). The sensory analyses resulted in odour descriptors such as cocoa, oat porridge and øllebrød (traditional Danish dish, a porridge based on bread scraps). Flavour/taste descriptors such as sweet, bitter, oat porridge and øllebrød were common for all wheat products. However, the intensity of the sensory attributes varied between the varieties. The ancient species, eg spelt, emmer and einkorn were sensorially characterised to have a mild aroma, odour and flavour of oat porridge. While some of the more modern wheats had a stronger aroma of øllebrød, wild rice, cocoa, vanilla and sweet. The old variety Kamut@khorasan was characterised as having an intense aroma and a sweet taste (Starr et al., 2013). From gas chromatography analyses, 88 volatile compounds were identified and out of them twenty two could be associated with the sensory descriptors. The following identified compounds were associated with sensory descriptors: 2-pentylfuran, benzaldehyde, 6-methyl-5-hepten-2-one, 2-methyl-1-butanol, 3-methyl-1-butanol, 2-methylbutanal, 2-nonenal, hexanal, and hexanol. Both sensory profiles and volatile compound profiles indicated a large variation among the wheat varieties. The resulting volatile and sensory profiles showed that ancient varieties were distinguishable from modern. It was further found that varieties from different countries could be distinguished from each other. It was suggested that wheat volatile composition has genetic causes (Starr, 2015).

When baking sourdough bread, it is well known that the flavour of bread is influenced by the combination of flour, the fermentation and the baking process. In a study of sour dough bread based on spelt and emmer compared to wheat bread, it was found that both spelt and emmer sourdough breads received the highest scores for acid taste. However, a clear preference for the overall taste was assigned to spelt sourdough bread (Coda et al., 2010). Emmer has been found to be suitable not only for bread baking, but also for making fermented functional beverages in which sensory attributes such as acidic, cereal and sweet were considered important (Coda et al., 2011).

Millet, an ancient African/Asian crop, may be used instead of wheat in, for example, cous-cous. Although the taste was found to be very bitter, other taste and flavour attributes, such as nutty, salty, buttery, sweet, salty aftertaste, were also found to differ significantly when comparing conventional couscous to millet couscous and, with the exception of sweetness, were significantly higher in the millet couscous than the conventional couscous (Sanderson et al., 2017).

An overview of the sensory aspects of cereals is presented in Table 3.

5.2. Texture and colour

The comparison of results from instrumental analysis with sensory analysis often shows good correlation regarding textural characteristics, and the hardness of crumbs from wheat loaves measured with a texturometer may be considered as an index of the total textural attributes of breads (Scheuer et al., 2016). Whole wheat spelt flour T.90% (expressing the milling yield) has been shown to differ from common white wheat flour T.70% when used in bread baking. The bread contained the ingredients: flour, sugar, salt and yeast. The bread made with spelt flour exhibited decreased volume, lower specific volume, darker crumb and crust colour, and increased crust and crumb hardness. Sensory characteristics that were considered to be less appealing. Spelt contains a higher protein content and different protein fractions compared to white wheat flour, which may explain some of the differences in bread based on spelt compared to white wheat (Frakolaki et al., 2018). Further, it has been shown that flour from organically grown wheat varieties, spring wheat, winter wheat and spring emmer, have a great variation in sensory characteristics within and between each variety. This was shown in products such as bread, pastry, pasta and cooked grain especially for texture and mouthfeel attributes. The study pointed out the complexity and the diversity of the wheat qualities. The differences were considered to be due to genotype by environment and genotype by milling interactions influencing quality for organically grown wheat (Kucek et al., 2017). Bread based on Kamut©khorasan flour showed sensory properties and loaf volumes very similar to bread made using modern wheat (Pasqualone et al., 2011).

In a study on bread baked with einkorn, durum and bread wheat, colour was compared. The breads were baked according to an optimised dough bread making method, AACC 10-10 B. The results showed that einkorn gave a lighter crust colour than bread wheat and durum wheat. It was suggested that einkorn undergoes lower heat damage than modern wheat during baking because low levels of α- and β-amylases limit the degradation of starch (Brandolini & Hidalgo, 2011). As a result, the reduced generation of reducing sugars in the dough limits the Maillard reactions during food processing. Low lipoxygenase activities in einkorn dough also limit the degradation of carotenoids (Hidalgo & Brandolini, 2014). Further, it was shown that einkorn had higher peak viscosity and final viscosity than modern wheat. These differences could probably be related to the smaller size and different grading of einkorn starch granules as well as to a lower amylose percentage in einkorn flour (Brandolini & Hidalgo, 2011).

In sourdough bread the fermentation process has a large impact on the sensory attributes of the bread, i.e., decreased cell uniformity, brighter, less elastic, but more cohesive fresh bread crumbs, with slower firming and starch retrogradation kinetics. This could be explained by the accumulation of both protein- and starch-bound lipids during fermentation and baking as well as slower starch hydrolysis (Collar & Conte, 2017). It was found that Kamut©khorasan was more suitable than durum wheat for the fermentation processes in acidic conditions, since an increase in bread volume and metabolic heat production by yeast were observed for kamut (Balestra et al., 2015).

When investigating alternatives to wheat flour in couscous, millet couscous samples differed significantly from conventional couscous. Millet is a crop with long traditions in Asia and Africa. The analysed texture attributes included cohesiveness, dryness and tooth-packing. It was also found that the type of cooking process impacted differently on the millet couscous. When cooked in a rice cooker, millet couscous was significantly higher in dryness and tooth-packing than that made on the stove (Sanderson et al., 2017).

An overview of the sensory aspects of cereals is given in Table 3.

Table 3
Sensory aspects of ancient grains.

Species	Product	Appearance	Taste/Flavour	Texture	Panel	Reference
Wholemeal wheat	bread		cocoa, grain, hazelnut, bitter, sour, salt		trained analytical	Starr (2015)
Emmer	sourdough bread		acidic		consumer	Coda et al. (2010)
	sourdough bread	low air bubble size	medium intense bread taste	medium rough surface, hearty crumb, grainy and low dryness	trained	Kucek et al. (2017)
	fermented functional beverages		acidic, cereal, sweet		trained	Coda et al. (2011)
	pasta	medium shiny		medium sticky, firm and grainy	trained	Kucek et al. (2017)
	cooked grain			medium dry	trained	Kucek et al. (2017)
	cracker	medium jagged		medium rough, grainy and firm	trained	Kucek et al. (2017)
Spelt	bread	low in volume, dark crumb and crust			consumer	Frakolaki et al. (2018)
	bread			crumb elasticity, low crumb homogenity	trained analytical	Callejo et al. (2015)
	bread	high volume, crumb whiteness		cohesivness (dough)	consumer	Angioloni and Collar (2011)
	bread	dark crust	sweet and salt, low bitter and acid	cohesive crumb	trained analytical	Pasqualone et al. (2011)
	sourdough bread		acidic		consumer	Coda et al. (2010)
Einkorn	bread	light colour		high viscosity (dough)		Brandolini and Hidalgo (2011)
Khorasan	bread	dark crust, yellow crumb	low sweet, bitter and acid, salt	cohesive crumb	trained analytical	Pasqualone et al. (2011)
	bread	high volume, crumb whiteness		cohesivness (dough)	consumer	Angioloni and Collar (2011)
Millet	couscous		very bitter, nutty, salty, butter and sweet	Cohesive, dry and tooth-packing	trained analytical	Sanderson et al. (2017)

5.3. Consumer attitudes and acceptance

Local and regionally produced crops, including ancient crops, are current consumer trends. These crops may provide new, interesting and tasty products with health-promoting ingredients, while at the same time increase crop and food diversity. These consumer trends further support small and medium-sized farmers, millers, traders, and end-product manufacturers. The products have the possibility to reach unique market positions compared with industrial mainstream products. The identification of ancient crop species best suited to current consumer and market needs requires an intensification of interdisciplinary research and long-term funding of undervalued crops (Longin & Würschum, 2016). However, it should be remembered that when selecting the best variety of ancient crop, it is important to consider the products that will be made from that specific variety, with its specific qualities (Kucek et al., 2017).

It has for example been shown that the variety with the highest preference or taste intensity as a cooked grain received the lowest rating as a processed product and significant interactions between variety and product has been statistically demonstrated. For example, for an emmer variety, the likelihood of preference for its nutty, fresh and earthy flavours depended on whether the variety was tasted as a cooked grain or pasta ($P < 0.05$) (Kucek et al., 2017). Bread loaves based on wheat, kamut or spelt were characterised by high palatability scores as well as high values for dough cohesiveness, high volume, crumb whiteness index and an open crumb structure (Angioloni & Collar, 2011). Flakes and muesli made from kamut and spelt also had acceptable sensory features, i.e., appearance, consistency and flavour, compared to their commercial sister products; it could further be noted that the flake and muesli products were high in total phenolic, flavonoid, and crude fibre contents (Sumczynski et al., 2015).

A comparative study with five different spelt varieties in the form of bread showed acceptable sensory scores, however with significant differences between the five varieties. The study also showed significant differences between different harvest years, and it could be concluded that weather conditions had a significant impact on flour and bread quality, as well as on texture liking (Korczyk-Szabó and Lacko-Bartosova, 2013). Comparing spelt varieties in the form of pasta, the results concluded that most spelt varieties might be suitable raw materials for pasta production, but differences in texture are closely related to the specific spelt variety (Korczyk-Szabó and Lacko-Bartosova, 2015). However, when comparing bread based on spelt to bread based on common wheat, it was found that spelt gave the bread a higher crumb elasticity, but low crumb cell homogeneity, probably due to special rheological attributes of the spelt dough (Callejo et al., 2015). Specific volume and crumb attributes of breads baked with spelt showed higher resemblance to breads based on commercial wheat than emmer did. Consumer studies showed that both spelt and emmer can be made into acceptable bread products (Coda et al., 2010). Pasta made from 100% emmer had an improved organoleptic value and lower glycaemic index than durum pasta (Fares et al., 2008).

Table 3 gives an overview of the sensory aspects of cereals.

5.4. Possibilities for improving sensory characteristics

Multigrain blends, i.e., mixtures of oat, rye, buckwheat and common wheat flours, appear to be a simple, efficient and useful strategy to obtain enhanced value, grain-based, baked goods such as bread. The quality profile yields added value due to increased nutritional content, high palatability, convenience and easy handling as well as high acceptability by consumers (Angioloni & Collar, 2011). However, substituting durum or/and common wheat flour with ancient wheat-based flour for the creation of new products may not suit modern and industrial processing methods. Thus, technological processing and formulations need to be improved to fit the compositional and morphological characteristics of the old varieties. Through this, ancient grains might constitute an alternative to modern varieties (Boukid et al., 2018).

Fermentation, i.e., sourdough baking, is a way to improve bread quality. Different Lactobacillus strains were used in sourdough bread based on ancient grains, e.g., quinoa and Kamut©khorasan flours, and compared to bread made from 100% wheat flour. Good acidification and a heterogeneous aromatic profile were recognised in all the doughs. Lactobacillus paracasei I1, in particular, contributed positively to the aromatic profile of the doughs, independently of flour type, producing the highest amount of ketones such as diacetyl, acetoin, 2,6-dimethyl-4-

heptanone, 5-methyl-3-hexanone, 4-methyl-3-penten-2-one. Volatile compounds were highly appreciated in the bakery products for their buttery, fatty and fruity notes (Di Renzo et al., 2018).

Hydrocolloids may be used to improve dough performance based on ancient grains. Hydrocolloids have the ability to improve bread volume, crumb porosity and texture, leading to products with enhanced sensorial and technological texture qualities, which may be useful in the development of new products based on ancient cereals. Positive effects have been found by the use of carboxymethyl cellulose, hydroxypropylmethyl cellulose, Kappa carrageenan, Lambda carrageenan, xanthan gum, guar gum and high methoxyl pectin at levels varying from 0.1% to 2.0%. The effects are based on the ability of hydrocolloids to increase the water absorption of wheat flour (Ferrero, 2017).

6. Future perspectives and recommendations for further research

Presently, there is no universally accepted definition of ancient and heritage cereals, although several attempts have been made. Ancient cereals often include cereals that have basically remained unchanged over hundreds or thousands of years. A standard definition for ancient cereals should be adopted. This would facilitate labelling of ancient cereal-containing foods and increased consumer trust.

Generally, ancient cereals appear to have great potential to become part of a healthy human diet. They can contribute to enhanced nutrient availability in the diet and to the provision of palatable, tasty food products. A number of new food products could be developed, where health benefits, environmental sustainability and attractive sensory properties are highlighted. Further studies should encourage consumers to reconsider the impact of products based on ancient cereals on improving dietary habits.

In addition, ancient grains are potential crops for environment friendly organic farming with a high resilience to climate change. So far, the scientific community has mainly focused on the positive contribution of ancient cereals to human health and the environment. Studies on the safety aspects of ancient cereals are, however, limited. For example, the levels of contaminants in ancient cereals and any potential risk following their consumption should be further studied.

Moreover, comparison of the yield of ancient and modern cereals warrant further investigations in order to predict their price when available in the market, and determine the potential commercial success of this group of cereals.

Acknowledgements

This study was financially supported by Formas, project no 2018–02393. We also gratefully thank Jenny McGreevy for skilful and efficient proofreading of the article.

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