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REVIEW PAPER

SORGHUM AS SOURCE OF FUNCTIONAL COMPOUNDS AND THEIR IMPORTANCE IN HUMAN NUTRITION

DANIELA IONELA ISTRATI[a], OANA EMILIA CONSTANTIN[a], CAMELIA VIZIREANU[a], DINICA RODICA[b], BIANCA FURDUI[b*]

[a]*University "Dunărea de Jos" of Galati, Faculty of Food Science and Engineering, no.111, Domneasca str., 800201, Galati, Romania*

[b]*University "Dunărea de Jos" of Galati, Faculty of Science and Environment, no.111, Domneasca str., 800201, Galati, Romania*

**corresponding author: bianca.furdui@ugal.ro*

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Due to the progress made in preventive medicine, it has been possible to highlight the key role of nutrition in the prevention of diseases, especially those related to diet. The general concern for the development of functional foods has generated the need to study and use new food ingredients involved in maintaining and improving the health condition. Sorghum is one of the most important grain considering the cultivated land areas and global production. Also, sorghum is a gluten-free grain and a rich source of nutrients and biologically active compounds. In this context, sorghum has a huge potential for its exploitation and development of healthy and functional food products. Therefore, this review summarizes the information regarding the concept of the functional food, as well as the role of functional compounds which are found in food products, especially in sorghum grains, and beneficial effects on human health.

Keywords: functional foods, health, nutrients, fibers, antioxidants

Introduction

Food is an environmental factor indispensable to the human body. Its daily consumption is necessary to meet everyday needs. This intake takes place in the form of solid and liquid food. Foodstuff is complex, natural substances that have undergone a technological and/or culinary treatment, preserved with or without special treatment (Opopol *et al.*, 2006).

Lately, an increase in terms of consumer interest in the importance of healthy food or physiologically active specific components called functional food was registered (Hasler, 1998).

The term functional food was introduced by Japanese researchers in 1984, who studied the relationship between nutrition, sensory satisfaction, fortification, and

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modulation of physiological systems. Different definitions of functional food can be found around the world, but there is no official definition. Therefore, a functional food product can be a natural food, a food product where a component was added to or out of which a component was removed, a food including one or more components whose nature was altered or any combination of these possibilities (Wang and Li, 2014). Functional food products can offer health benefits when consumed at adequate levels in a regular diet (Sharanya Rani and Penchalaraju, 2016). The functionality of food may be similar for all individuals or for a specific population, defined, for example, by age or genetic structure. Moreover, functional foods, in addition to their primary nutritional effect, also have a positive influence on the functions of the human body (improvement of general physical condition, reduction of disease risk, etc.) (Roberfroid, 2000, Howlett, 2008; Ozen *et al.*, 2012).

Up to date, Japan is the only country that has formulated a system of standards and registration and approval specifications for functional foodstuff, known as Foods for Specified Health Use (FOSHU). These food products are eligible to carry a seal of approval from the Japanese Ministry of Health and Social Protection (Arai, 1996). At present, 100 products are licensed as FOSHU foods in Japan.

The European Commission's Concerted Action on Functional Food Science in Europe (FUFOSE) has defined functional foods as follows: "A nutrient can easily be considered a functional food only if it was satisfactorily proven that one or more target functions can be changed positively, in addition to nutritional effects, to constantly improve health and well-being while reducing the risk of any illness. A functional food should ideally be a nutrient and should not change its efficacy when it enters a diet; it should not be a pill or capsule" (Scientific Concepts of Functional Foods in Europe). The same committee concluded that basically, functional food could be one of the following:

- a natural food;
- a food product with an addition of one component added;
- a food that no longer contains one of the components;
- a food product in which one or more components have been changed;
- a food product in which the bioavailability of one or more components has been modified;
- any combination of the previous features.

Worldwide, a relatively large number of terms are used to define natural products developed for health benefits: functional foods, nutraceuticals, pharmafood, designer food, vitafood, and foodceuticals (Roberfroid, 2000; Constantin and Istrati, 2018).

Current foods incorporate a growing volume of technical and scientific progress. As a result, modern food technology is distinct from the classical one. The critical areas for the technological challenges that were identified are as follows:

- creating new functional nutritional elements out of traditional raw materials;
- optimizing functional nutrients out of raw materials and foods - for instance: preservation or maximum retention of elements;
- altering their function and their high bioavailability;
- monitoring of the quantity and effectiveness of functional nutrients in the raw materials and food.

Irrespective of the production technology, foods are made up of several basic ingredients, called nutrients that fall into two categories:

- macronutrients in the broad sense: proteins, lipids, carbohydrates, some minerals, the intake of which is indispensable in significant quantities (in the tens of grams or even grams per day);
- micronutrients (most of the vitamins and minerals, the intake of which is in the range of micrograms or milligrams per day).

Macronutrients consist most often in large molecules and complex structures that require a prior breakdown (digestion) into molecules that are small enough and simple to be absorbed. Proteins are sources of amino acids, lipids - fatty acids, cholesterol, glycerol, etc.; complex carbohydrates are sources of monosaccharides, like glucose, galactose, fructose, xylose and its derivatives, such as the sorbitol, etc. Proteins, carbohydrates, and lipids are "nutrient source molecules" and are absorbed after preliminary digestion. Amino acids, fatty acids, cholesterol, various monosaccharides, vitamins, and minerals are considered "cell nutrients" and are absorbed directly without prior digestion (Opopol *et al.*, 2006).

The nutrient content gives the nutritional value of foods, along with their quality, bioavailability, and the way consumers are physically satisfied (Segal, 2002). In addition to macronutrients, the human body also needs other components of nutritional interest: food fibres and various compounds such as tannins, phenolic compounds, various organic acids (that are to be found mainly in vegetables) that can exert an influence on digestion, absorption and sometimes on the metabolism of nutrients (Opopol *et al.*, 2006).

Therefore, functional foods are products that contain various biologically active compounds and which – provided that they are consumed in a current diet - contribute to maintaining the optimal state of physical and mental health of the population.

Recent epidemiological studies demonstrated the beneficial effect of whole grains and cereal products on medical conditions such as type II diabetes, obesity, coronary heart disease, cardiac disease, and certain cancers (McCarty, 2005, Yu and Nanguet, 2013). Cereals and grain products cover about 50% of the daily energy required for a person. This nutritional intake can provide 50% of the daily protein requirement, 25% calcium, 50% iron, and 40% vitamin B (USDA, 2019).

Sorghum (*Sorghum bicolor*) is a cereal that belongs to the *Gramineae* family being cultivated for the first time about 4000 years ago in North-East Africa (Rooney and Waniska, 2000). There are several varieties of sorghum from white to yellow, brown, red and black. Sorghum is one of the most important cereals in the world, ranking fifth in terms of global cereal production by corn, wheat, rice, and barley. In 2017 the annual production quantity of sorghum was estimated to be 57.6 million tons grain from an area harvested of 42.67 million hectares (FAO, 2017).

Researches have shown that sorghum whole grains have substantial health benefits as a result of its high nutritional value and to the unique profile of phenolic compounds (Khan *et al*., 2015; Khoddami *et al*., 2015, Rao *et al*., 2018, Xiong *et al*., 2019). The variations of climatic conditions during the growing period of the crop along with crop varieties, soil type, fertilizers and method of fertilization influence the chemical and nutritional composition of sorghum (Ebadi *et al*., 2005). According to USDA (2019), 100g of sorghum grain contains on average 10.6 g proteins, 72.09 g carbohydrates, 6.7 g fibers, 3.46 g lipids and provides 1377 kJ energy. The unusual composition of sorghum phenolic compounds (phenolic acids, 3-deoxyanthocyanins, flavones, flavanones, and condensed tannins) and their high level reported in sorghum bran, make sorghum an interesting cereal for the production of healthy functional foods, as a source of bioactive compounds.

The functional role of proteins within human nutrition

Proteins are the fundamental constituents of living cells. Growth, reproduction, and nutrition, which are essential functions of the living matter, are related to proteins and their metabolism products: peptides and amino acids (Shang *et al.*, 2018; Opopol *et al.*, 2006). Therefore, proteins have various functions, such as:

- structural role, as components of all the cells, necessary to growing and restoring tissues ;
- taking part in metabolic processes, in regulating the hydro-electrolytic and the acid-base balance, they are structural components of various enzymes and hormones and thus have a functional role. They can also perform specific functions – antibodies;
- energetic role.

Proteins of animal origin are more equilibrated in indispensable amino acid content in comparison to proteins of vegetable origin. In terms of the indispensable amino acid content, proteins are divided into three categories:

A. proteins with superior biological value - which contain all essential amino acids in adequate proportion to the human body (most of the animal proteins);
B. medium-quality proteins – which also contain all essential amino acids, but some in insufficient proportions (vegetables, fruits, dried legumes, cereals);

C. low biological value proteins lacking one or more essential amino acids (for example zein, the main maize protein, is depleted of lysine and very poor in tryptophan, while collagen is tryptophan-free, low methionine, isoleucine, lysine, and threonine) (Damtie, 2019; Paul *et al*., 2019; Murano, 2003).

The required amount of protein depends on the needs of the body's development and their biological value, according to the diet. The recommended intake is based on the amount of protein required to maintain the balance between the amount of nitrogen consumed as protein and the nitrogen eliminated daily.

The total protein intake should be 10-15% (20% maximum) of the total calories with a optimal dietary protein intake for adult people of 0.66 g protein/kg/day and for older people a optimal dietary protein intake of 1.2 g protein/kg/day (Rand *et al*., 2003; FAO, 2013; Bauer *et al*., 2013).

The protein deficiency leads to a drop in the metabolic capacity, to reduced energy metabolism, to the inhibition of biosynthesis processes, to a diminished immunity, and body resistance to external agent actions, accordingly. Usually, the required protein is influenced by gender, age, activity level, and body health or physiological condition (Wolfe *et al.*, 2017; Dullius *et al.*, 2018). Conventional sources of protein are products of animal and plant origin such as meat, milk, eggs, fish, cereals, etc. (Dullius *et al.*, 2018).

Sorghum proteins can be divided into two categories: prolamine proteins (kafirins are the main form of protein storage in sorghum grain and represents about 80% of total protein) and non-prolamine proteins (globulins, glutelins, and albumins which represent 20% of total protein). Depending on the molecular weight, there are four types of kafirins α-, β-, γ -, and δ-kafirin. Sorghum prolamines are characterized by a high content of glutamic acid, leucine, alanine, proline, and by a low content of lysine, which represents only 0.2% of the total amino acids (Serna-Saldivar and Rooney, 1995; Xiong *et al*., 2019; UDSA, 2019). However, sorghum lysine deficiency can be ameliorated by breeding or fortification (Henley *et al*., 2010; Grootboom, 2010).

Sorghum proteins are characterized by reduced digestibility because kafirins have high levels of polymerization and extensive disulfide bridges which are resistant to enzymatic digestion. Also, the interaction of sorghum proteins with tannins and starch leads to decreased digestion. Due to the low digestibility of starch and protein, sorghum can be used as a food source for people with obesity and diabetes. Moreover, kafirin (as a gluten-free ingredient) is used to develop healthy food products for people with celiac disease (Belton *et al*., 2006).

The functional role of bioactive lipids in human nutrition

Lipids are a family of water-insoluble compounds with particular properties, determined by the structure and the physio-chemical characteristics of the various molecules in their composition. Lipids play essential roles in the body, particularly in maintaining the integrity of cell membranes, in nervous transmission, and in the process of absorbing nutrients. Food lipids are composed of esterified fatty acid molecules in the form of triglycerides and phospholipids. Food sterols are mainly represented by cholesterol and sterols of plant origin (phytosterols).

On the other hand, depending on the hydrogen saturation of their molecule, fatty acids are classified as saturated and unsaturated. Unsaturated fatty acids may be mono - or polyunsaturated. Fats of animal origin contain more saturated fatty acids, and those of vegetable origin have unsaturated fatty acids, the latter showing cardiovascular protective properties. Cholesterol is a necessary substance for the body and is found only in foods of animal origin, but it can also be synthesized in the body.

The investigations conducted to elucidate the role of lipids in human food showed that these nutrients possess first-order biological properties due to their intake in biologically active compounds such as polyunsaturated fatty acids, phosphatides, sterides, vitamins D, etc. (Segal, 2002). Besides the role of the lipid as a high-calorie source, structural constituents of biomembranes or as solvents and vehicles of lipid-soluble vitamins, are important by their intake of polyunsaturated fatty acids, phosphatides and physiologically active substances such as prostaglandins, prostacyclins, etc. (Hansen, 1994). It is already known that the polyunsaturated fatty acids (omega-3 and omega-6) are essential for human health and are exclusively obtained from food (Rubio-Rodríguez *et al.*, 2010). In recent years, the importance of making functional foods supplemented with n-3 fatty acids was highlighted. There is currently a wide range of omega-3-enriched foods such as bakery products, dairy products, soft drinks and juices, meat products, etc. (Kolanowski and Laufenberg, 2006). Typically, the natural sources of n-3 fatty acids are some seeds and fish oils (Rubio-Rodríguez *et al.*, 2010; Jiménez-Colmenero, 2007).

Healthy eating should not contain a lipid contribution of more than 30% of the total daily energy intake. Of these, less than 10% will be provided by saturated fatty acids, 10% by the monounsaturated fatty acids, and 10% by the polyunsaturated fatty acids as cis. During the last decade, the scientific studies concluded that consumption of 1-2 g/day of polyunsaturated fatty acids is required for maintaining the state of health. It was shown that polyunsaturated fatty acids have a beneficial effect in some diseases, such as rheumatoid arthritis and atopic dermatitis (FAO, 2010; Hooper *et al*., 2015).

Sorghum lipids consist mainly of unsaturated fatty acids, of which the most abundant are polyunsaturated (monounsaturated fatty acids represent 1.131 g/100 g and polyunsaturated fatty acids 1.558 g/100g). The main sorghum fatty acids are oleic, palmitic, linoleic, stearic, and linolenic (Adeyeye and Ajewole, 1992; USDA, 2019). Sorghum lipids such as phytosterols and polycosanols were shown to protect against cardiovascular disease by regulating cholesterol metabolism (Carr *et al*., 2005; Hoi *et al*., 2009; Martınez *et al*., 2009).

The functional role of vitamins and minerals in human nutrition

Vitamins are organic compounds with a complex structure that cannot be synthesized by the human body. Their presence in the body is essential for the fulfilment of essential functions of the body. Vitamins are required in minimal amounts for the normal development of many metabolic processes, including assimilation and use of nutrients, food growth, and tissue restoration (Gould, 1995). Unlike proteins, lipids or carbohydrates, vitamins are not sources of calories and are needed in much smaller quantities. Depending on how they are dissolved in various solutions, vitamins are classified into liposoluble (vitamins A, D, E, and K) and water-soluble (vitamins falling into group B and vitamin C). Water-soluble vitamins are particularly useful in energy-releasing reactions, and liposoluble ones are more involved in metabolic processes and the formation of certain body-specific substances (Segal, 2002).

Sources of vitamin B1 are germs of cereals, nuts, whole grains, beer yeast, etc. Vitamin B1 has several essential functions in the body, such as: maintaining a regular appetite and digestion, also useful in terms of growth and lactation (Gould, 1995). Vitamin B2 (riboflavin) is found in bakery yeast, eggs, meat, fish, and dairy products. In the human body, riboflavin performs specific metabolic functions in the glucose metabolism (glucose and galactose are rapidly absorbed only in the presence of riboflavin) but also in the lipid and amino acid metabolism (Combs and McClung, 2016). Vitamin B5 is found in wheat germ, oats, broccoli, mushrooms, cauliflower, dried peas, soybeans, etc. As coenzyme A, riboflavin has a vital function in different metabolic pathways, such as carbohydrates and lipids metabolism (Combs and McClung, 2016). Vitamin B6 participates as a coenzyme in the form of pyridoxine and pyridoxal to the activity of transaminases, having an important role in the metabolism of amino acids. Pyridoxal and pyridoxamine are coenzymes involved in transamination, decarboxylation, melanin formation, tryptophan metabolism, transmethylation, porphyrin synthesis, and others (Saghiri *et al.*, 2017). Important sources of vitamin B6 are meat, liver, fish, beans, nuts, baker's yeast (*Saccharomyces cerevisiae*), cereals, etc.

Vitamins E (tocopherol) exerts more functions in the body by participating in the proper functioning of specific apparatuses and systems such as the reproductive, the cardiovascular, and the muscular one. It is also a biological antioxidant for oxidable vitamins and lipids (Combs and McClung, 2016). High amount of vitamin E are found in vegetable oils, cereal-based products, and eggs.

Vitamin C (ascorbic acid) plays a significant biological role, its field of activity being wide to such an extent that it can be appreciated that there is no essential physiological or metabolic process to which it does not participate (Segal, 2002). Vitamin C acts as a biochemical antioxidant (Combs and McClung, 2016), interfering with many processes, including protein metabolism, stromal protein formation (collagen, elastin), carbohydrate metabolism (it inhibits cholesterol synthesis and prevents the development of atherosclerosis), lipid metabolism (reduces blood cholesterol), etc. Sources rich in vitamin C include vegetable products such as citruses, tomatoes and tomato juice, cabbage, parsley, nettle, spinach, cauliflower, red and green peppers, red cabbage, eggplants, broccoli, strawberries, (Saghiri *et al.,* 2017; Sinha *et al.*, 1993).

Minerals are inorganic substances with a simple structure (non-fractional), which the body has to acquire from food because it cannot synthesize them as such. As with vitamins, minerals perform essential functions in the human body without being sources of calories and are needed in much lesser amounts than proteins, lipids, or sugars (Ihnat, 2003)

The mineral substances necessary to the body can be classified into two categories of macroelements (found in the body in considerable quantities: calcium, phosphorus, magnesium, sulfur, chlorine, potassium and sodium) and microelements or trace elements (found in small or extremely small quantities: iron, copper, chromium, manganese, zinc, cobalt, molybdenum, nickel, tin, silica, arsenic, selenium, fluoride and iodine). The distribution of minerals in food is irregular. Some minerals, like potassium and sulfur, are abundantly spread in the food, so a varied diet always contributes sufficiently.

Mineral elements have a critical biological role considering that they participate in all the vital processes of the body. Mineral substances may have different roles in the vitamin and enzymes operation, either having an activating role (calcium, magnesium, etc.) or an inhibiting role (copper) and may be part of the specific enzyme structure (sulfur, iron, copper, etc.) or non-specific elements (magnesium, zinc, cobalt, etc.) (Hathcock, 1997).

From the whole vitamins mentioned above, the principal vitamins in sorghum grains are B complex vitamins that play a major role in energy metabolism (thiamin, pyridoxine, and riboflavin), and alpha-tocopherol. Moreover, sorghum is a good source of minerals whose bioavailability varies from less than 1% for Fe to over 90% for K and Na. Therefore, the main minerals in sorghum are potassium, phosphorus, magnesium, and zinc (Leder, 2004; Ratnavathi and Patil, 2013; USDA, 2019). Compared to rye and barley, sorghum has a lower composition in P, Mg, K, Na, Ca, Fe, Zn, Mn, and Cu, similar to millet (Ragaee *et al*., 2006). Worldwide there are four micronutrients at risk, which represent a problem of human nutrition, namely iron, zinc, iodine, and vitamin A. Sorghum is a good source of iron and zinc and can be used in programs to combat malnutrition in the population of developing countries (Nguni *et al*., 2011).

The functional role of dietary fibers in human nutrition

According to Regulation (EU) No. 1169/2011, the term "fibers" refers to carbohydrate polymers formed of three or more monomeric units that cannot be digested or absorbed at human small intestine level. They belong to the following categories:

1. carbohydrate polymers naturally occurring in foods;

2. carbohydrate polymers obtained from food raw materials by physical, enzymatic or chemical methods;

3. synthetic edible carbohydrate polymers with beneficial physiological effect demonstrated by generally accepted scientific evidence.

Food fibers have many beneficial effects on health: reducing the intestinal transit time, diminishing the total cholesterol and/or LDL levels in the blood, reducing postprandial blood sugar and/or insulin levels, etc (Mehta, 2005). Because of these effects, they can prevent colon cancer, diabetes, constipation, ischemic heart disease, myocardial infarction, obesity, dental caries (Cade and Burley, 2007; Spotti and Campanella, 2017), improve gastrointestinal health and reduce sensitivity to certain diseases. Increased consumption was also associated with increased satiety and weight loss (Georgescu, 2004). The recommended fiber intake should be 20-30 g/day. Ingestions higher than 30 g/day may cause disturbances accompanied by bloating and abdominal pain (Opopol *et al*., 2006).

Rich sources of fiber are whole grains, dried peas, beans, vegetables, nuts, and fruits. Sorghum is an excellent source of dietary fiber ranging from 6 g to 8.6g/100g (USDA, 2019). According to Awika *et al*. (2005), the dietary fiber content of the cereals is about 45% in the bran and represents up to 6 times more than the level measured in the endosperm. Therefore, fractions of sorghum bran contain on average 36–50% total dietary fiber from which 35 – 48% insoluble dietary fiber (Rooney *et al*., 1992). In studies conducted to obtain functional food products (such as bread, cakes, and expanded snacks) with the addition of sorghum bran, it was shown that it confers an attractive natural color with no negative impact on other sensory properties of foods (Gordon, 2001; Acosta *et al*., 2003). Dietary fibers from sorghum may play a crucial role in the development of healthy food products due to the growing need for diversification of functional foods (Miafo *et al*., 2015).

The functional role of polyphenols in human nutrition

Polyphenols are one of the most common and widespread groups of herbal substances that appear in all vegetative organs. These are secondary metabolites in plants, in response to ultraviolet rays, to the aggression of pathogens (Beckman, 2000). More than 8.000 phenolic structures out of which more than 4.000 flavonoids (Harborne, 2000; Cheynier, 2005) were identified by now.

Classification of polyphenols was quite difficult to achieve due to the large variety of these compounds. Tsao (2010) gave the most common classification according to the chemical structure: phenolic acids, flavonoids, stilbens, and ligands, while Shalaby and Shanab (2013) gave a different classification as following: flavonoids and phenolic acids. Flavonoids are polyphenolic compounds, including two benzene rings connected by a ”bridge”. The main subclasses of these compounds are flavones, flavonols, flavan-3-ethanol, isoflavones, flavanones, and anthocyanidins. Other groups of flavonoids, which are smaller food components, are chalcones, dihydrochalcones, dihydroflavonols, flavan-3,4-diols, coumarins, and aurones (Del Rio, 2013). The main subclasses of phenolic acids are hydroxi-cinnamic and hydroxibenzoic acids (Shalaby and Shanab, 2013).

Polyphenols and flavonoids have proved to have many beneficial effects on health: antioxidant and free radicals capturing property, anti-atherosclerotic, cardio-protective, neuroprotective, anti-aging, anti-neurodegenerative, anti-inflammatory, anti-mutagenic, anti-cancer, improving endothelial function, anti-allergic, anti-diabetic, anti-bacterial and hepato-protective function (Han *et al.*, 2007).

Sorghum contains both phenolic acids and flavonoids, which are found in pericarp, testa, and endosperm. Phenolic acids in the sorghum grains are found in bound (70–95% of the phenolic acids are associated with polysaccharides from the cell wall) and free forms. Free phenolic acids aren`t linked with the cell wall and are found especially in pericarp and testa. They often conjugate with glycerol and carbohydrates (Svensson *et al*., 2010; Taylor *et al*., 2014). The most important phenolic acids reported in sorghum are vanillic, gallic, cinnamic, protocatechuic, p-coumaric, syringic, p-hydroxybenzoic, caffeic, ferulic, and sinapic acids (Althwab et al., 2015; Vanamala et al., 2018).

Flavonoids are the most abundant phenolic compounds reported in sorghum. These compounds are found mostly in bran and are responsible for pericarp color and pigmented testa. The main flavonoids reported in sorghum are anthocyanins (3-deoxyanthocyanidins), flavones, and flavanones which are more abundant, and flavan-3-ols, flavan-4-ols, flavonols, and dihydroflavonols (Dykes *et al*., 2005; Awika *et al*., 2005; de Morais Cardoso *et al*., 2017; Shen *et al*., 2018). Of the flavonoid class, anthocyanins are the most studied, due to their unique structure that gives them special properties. The main anthocyanins found in sorghum - 3-deoxyanthianine doesn`t contain the hydroxyl group at position 3 of the C ring. This unique feature leads to increased stability of 3-deoxyanthianine at high pH values which makes them usable in the food industry in the form of natural food colorants. The most important 3-deoxyananthocyanidins in sorghum are apigeninidine (responsible for the yellow color) and luteolinidine (responsible for the orange color) (Awika *et al*., 2004). The highest quantity of 3-deoxyanthianine is found in sorghum bran. Studies have reported contents up to five time higher of 3-deoxyanthianine in bran compared to whole grain. In some types of sorghum, the 3-deoxyanthianine content represents over 80% of the total amount of flavonoids. Moreover, of the sorghum genotypes, the black sorghum bran contains the highest amount of 3-deoxyanthianine (4,700 - 16,000 μg/g) as compared to the red (14-680 μg/g) and the brown one (3,600 μg/g) or with other cereals (blue barley 4 μg/g, red/purple maize 225–965, blue/purple wheat grain 35-507 μg/g or black rice 158-299 μg/g (Awika *et al*., 2004; Awika *et al*., 2005; Abdel-Aal *et al*., 2008; Hiemori *et al*., 2009).

Besides ensuring an attractive color from orange to red, blue, and purple, 3-deoxyanthianine has high antioxidant and antimicrobial properties with positive implications in human health. Sorghum is considered to be the main source of 3-deoxyanthianine for humans (Awika *et al*., 2004; Awika *et al*., 2005; de Morais Cardoso *et al*., 2017).

Other intensively studied sorghum polyphenols are tannins (condensed tannins or proanthocyanidins) which have potential health benefits due to their antioxidant capacity. Tannins are mainly found in both pericarp and cell walls but their concentration differs depending on the variety of sorghum. Depending on the genotype of the sorghum as well as the concentration of tannins and their degree of extractability, sorghum can be classified into three categories: a) Sorghum type I has recessive genes (B1, B2), has no pigmented testa and therefore has no tannins or very small amounts (0 to 1.8 mg CAE/g); b) Sorghum type II has the dominant B1 and B2 genes and recessive S genes, has pigmented testa with moderate amounts of tannins (6.4 to 15.5 mg CAE/g); and c) Sorghum type III has pigmented testa, all genes are dominant (B1, B2 and S), and high amounts of tannins (11 to 50.2 mg CAE/g) (Dykes and Rooney, 2006). According to Gu *et al.* (2004), the daily average dose of proanthocyanidins is estimated to be between 1.3 mg/day for infants, about 50 mg/day for children and young people, and over 70 mg/day for the men over 60 years of age.

Compared with other cereals such as wheat, rice or maize, the phenolic compounds extracted from sorghum have the highest antioxidant activity, the values being comparable to those obtained by fruits or vegetables (Wu *et al*., 2004). The antioxidant activity of sorghum is strongly linked to the total content of phenolic compounds and especially the condensed tannin content that is higher in black and brown sorghum (Awika *et al*., 2005; Dykes *et al*., 2005).

The antioxidant activity of sorghum biological active compounds was correlated with many beneficial properties for human health such as reduced oxidative stress (Khan *et al*., 2015), anti-cancer (Yang *et al*., 2009; González-Montilla *et al*., 2012; Suganyadevi *et al*., 2013) anti-diabetic (Kim *et al*., 2011; Kim and Park, 2012), anti-microbial (Kil *et al*., 2009), and anti-inflammatory activity (Burdette *et al*., 2010).

Conclusions

Functional foods include foods that contain fatty acids, dietary fiber, vitamins, and minerals as well as foods with containing biologically active compounds such as polyphenols, which exhibit high antioxidant activity. Studies on functional foods confirm that nutrition has a significant impact on the prevention of chronic diseases since most of these foods are consumed daily. Sorghum is one of the most important global grain crops which have high nutritional values with positive impact on human health. Although traditionally sorghum was used to obtain different foods such as boiled products, baked foods, steamed or fermented beverages, nowadays, due to advanced food science and technologies, both whole sorghum grains and its valuable functional compounds (phenolic compounds, bran, 3-deoxyanthianine, etc.) can be used to obtain healthy and functional food products.

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