Sorghum Grain: From Genotype, Nutrition, and Phenolic Profile to Its Health Benefits and Food Applications

Yun Xiong, Pangzhen Zhang, Robyn Dorothy Warner, and Zhongxiang Fang

Abstract: Globally, sorghum is one of the most important but least utilized staple crops. Sorghum grain is a rich source of nutrients and health-beneficial phenolic compounds. The phenolic profile of sorghum is exceptionally unique and more abundant and diverse than other common cereal grains. The phenolic compounds in sorghum are mainly composed of phenolic acids, 3-deoxyanthocyanidins, and condensed tannins. Studies have shown that sorghum phenolic compounds have potent antioxidant activity in vitro, and consumption of sorghum whole grain may improve gut health and reduce the risks of chronic diseases. Recently, sorghum grain has been used to develop functional foods and beverages, and as an ingredient incorporated into other foods. Moreover, the phenolic compounds, 3-deoxyanthocyanidins, and condensed tannins can be isolated and used as promising natural multifunctional additives in broad food applications. The objective of this review is to provide a comprehensive understanding of nutrition and phenolic compounds derived from sorghum and their related health effects, and demonstrate the potential for incorporation of sorghum in food systems as a functional component and food additive to improve food quality, safety, and health functions.

Keywords: functional foods, human health, nutritional composition, phenolic profile, sorghum grain

Introduction

Sorghum is a cereal of Poaceae grass family native to Northeastern Africa and was first cultivated from 3700 to 4000 years ago (Rooney & Waniska, 2000). Sorghum is one of the leading cereal crops worldwide and ranked the fifth highest production of the cereal crops, following maize, wheat, rice, and barley, with 57.6 million tons of annual production globally in 2017 (FAO, 2017).

Sorghum has been widely grown in tropical and subtropical regions. In Asian and African countries such as India and Nigeria, sorghum is one of the important crops and is used to make foods such as bread and porridges; especially in some under-developed and semiarid regions, it is the principal source of energy and nutrition for humans (Rooney & Waniska, 2000). In Western countries such as the United States, Mexico, and Australia, sorghum is mainly grown for animal feed. However, there is increasing interest in cultivating sorghum for biofuel production, as well as food for human consumption, due to the natural ingredients contained in sorghum, which are beneficial for the development of healthy and functional foods (Rooney, Portillo, & Hayes, 2013; Taleon, Dykes, Rooney, & Rooney, 2012).

Sorghum is well known for its outstanding agronomic performance, that is, adaptability to grow in a variety of environments. It is drought tolerant, heat tolerant, and can grow in high altitudes and saline–alkaline and barren soil. This is because sorghum has a well-developed root system with a high root to leaf ratio, and the leaves are protected by wax and can also roll themselves in response to external threat/stimulus (Rooney & Waniska, 2000).

In addition to its agronomic advantages, sorghum grain is gluten free, high in resistant starch and is a rich source of nutrients, and most importantly, contains a diverse range of bioactive phenolic compounds (Awika & Rooney, 2004; Dykes & Rooney, 2007). Sorghum contains more abundant and diverse phenolic compounds compared to other major cereal crops; it contains nearly all classes of phenolic compounds, with simple phenolic acids, flavonoids, and tannins being the dominant groups (Dykes & Rooney, 2007; Shen et al., 2018).

The unique phenolic profile confers sorghum with a number of human health benefits such as reducing oxidative stress and cancer prevention (González-Montilla, Chávez-Santoscoy, Gutiérrez-UrIBE, & Serna-Saldívar, 2012; Yang, Browning, & Awika, 2009). Because of the superior agronomic attributes and health potential, sorghum has attracted great attention from academia and food and drug industries for the past decades. With an ever-increasing shift in consumers’ demand toward healthy and plant-based food, sorghum has enormous potential for exploitation and development into healthy and functional foods and food additives. Attempts have been made recently to use sorghum whole grain or ingredients to make novel foods such as sorghum grain tea, as well as...
incorporating sorghum into foods, such as breads and meat products, to improve food quality and health benefits (Cabral et al., 2019; Wu et al., 2018; Xiong, Zhang, Luo, Johnson, & Fang, 2019).

Although there are several recently published reviews in the same area (de Morais Cardoso, Pinheiro, Martino, & Pinheiro-Sant’Ana, 2017; Girard & Awika, 2018), this review is comprehensive and provides important updates. Specifically, this review (1) provides detailed sorghum grain classification methods based on the properties of grain genotype, appearance, and phenolic profile; (2) summarizes the individual phenolic compounds (free or bound form) identified in different fractions of sorghum grain (bran or kernel), as well as their contributions to health; and (3) discusses the sorghum applications from traditional use to modern use, from the use of the whole grain to make functional foods to the incorporation of the whole grain or grain components to other food products. The concept of this review is illustrated in Figure 1, which provides an important insight into the selection of sorghum varieties/ingredients for different food applications to maximize its commercial value and health benefits.

**Sorghum Grain Structure, Genetics, and Classification**

Sorghum grain (naked caryopsis) is composed of three distinct main parts, which are the bran layer (pericarp and tests), the endosperm, and the germ (Figure 2); some sorghum varieties may have a pigmented testa located between the pericarp and endosperm (Earp, McDonough, & Rooney, 2004; Waniska & Rooney, 2000). In general, sorghum bran layer pericarp and tests contain nonstarch polysaccharides; a great variety of phenolic compounds including phenolic acids, flavonoids, and condensed tannins; and some vitamins such as carotenoids. The endosperm constitutes of mainly starch, proteins, and some vitamins (vitamin B complex) and minerals. The germ fraction is mainly composed of lipids and proteins, and is rich in vitamins (mostly vitamin B complex and fat-soluble vitamins) and minerals (Earp et al., 2004; Rooney & Waniska, 2000; Slavin, 2004). Among them, sorghum bran has attracted the most interest, because of its rich phytochemical content, especially the most prominent bioactive phenolic compounds 3-deoxyanthocyanidins and condensed tannins. The phenolic contents in the bran layer are up to six times higher than the whole grain, which presents a promising opportunity to be exploited as a functional food or food ingredient (Awika, McDonough, & Rooney, 2005).

The phenolic profile of sorghum differs greatly among varieties and depends on sorghum genotypes as well as the growth and environmental conditions (Wu, Johnson,Bornman, Bennett, Clarke, et al., 2016; Wu, Johnson, Bornman, Bennett, Singh, et al., 2016). Sorghum is highly diverse in genetics, and a wide range of sorghum varieties are available in various colors, sizes, structure, and shapes (Awika & Rooney, 2004; Bean et al., 2016), with more than 235,000 sorghum germplasm accessions having been collected globally (Aruna, Visarada, Bhat, & Tonapi, 2018). The color is closely related to the phenolic profile of the grain, particularly the bran layer of the grain, and is determined by the genes that control the pericarp color (R and Y genes), pericarp thickness (Z gene), presence of pigmented tests (B1 and B2 genes), spreader (S gene), testa color (Tp), and the color intensifier (I gene) (Rooney & Waniska, 2000). According to the color, phenolic profile, and genotypes, sorghum can be broadly classified into five types: white, yellow, red, brown, and black sorghums (Table 1).

White sorghum has a white or colorless pericarp when the Y gene is recessive, and irrespective of the R gene (rr yy).

White sorghum has low levels of total phenolic contents, and has very low levels, or zero levels, of tannin and 3-deoxyanthocyanidin (Awika & Rooney, 2004). Yellow sorghum has a yellow pericarp when the R gene is recessive and Y gene is dominant (rrYY). Yellow sorghum is rich in flavanones and has slightly higher total phenolic contents than white sorghum (Dykes, Peterson, Rooney, & Rooney, 2011). It should be noted that some white pericarp sorghums with a yellow endosperm may often be considered as yellow sorghum because of their yellow phenotypical appearance, but they are not genetically yellow. Sorghum with a red or black-colored pericarp has the genes R and Y both being dominant (RY YY). Red sorghum has moderately high levels of phenolic compounds but lacks tannins. Black sorghum is genetically red and is a special type of red sorghum, because the red pericarp changes into black under sunlight radiation during maturation. Black sorghum has high levels of phenolic contents that are concentrated in the pericarp, particularly the content of 3-deoxyanthocyanidins (Dykes, Rooney, & Rooney, 2013; Dykes, Rooney, Waniska, & Rooney, 2005; Dykes, Seitz, Rooney, & Rooney, 2009). Brown sorghum, also known as tannin sorghum, has pigmented testa and high levels of condensed tannins (Awika & Rooney, 2004). The presence of the tests in sorghum is regulated by the testa gene B1 and B2 but is irrelevant to the pericarp color genes (R and Y). The pigmented testa is developed in sorghum when the dominant form of B1 and B2 testa gene is present (B1 B2). Because the tests is brown/purple color, the pericarp appears to be a brown color phenotypically (Earp et al., 2004). However, the pericarp color and color intensity do not necessarily reflect the presence of condensed tannins in sorghum. Sorghum with a dark color pericarp may not contain condensed tannins, but sorghum with a pigmented tests must have the tannins; the presence of condensed tannins depends on the presence of pigmented testa (B1 B2; Dykes et al., 2011).

In addition, the color of sorghum grain is also influenced, to a lesser extent, by the pericarp thickness (Z), intensifier (I), testa color (Tp), and spreader (S) genes. The dominant Z gene (Zz) produces a thin pericarp, whereas the recessive Z gene (zz) gives a thick pericarp that is filled with starch granules in the mesocarp; the thicker the pericarp, the darker the color (Rooney & Waniska, 2000). The intensifier gene (I) influences the color intensity only in grain with red and yellow pericarp, and the dominant I gene (I+) increases the color intensity, whereas recessive I gene (ii) results in lighter colors (Earp et al., 2004; Rooney & Waniska, 2000). The testa color gene (Tp) controls the pigment color in testa, and the color of the testa is brown when Tp is dominant (Tp+) and purple when it is recessive (ttpp) (Dykes & Rooney, 2006). The spreader gene (S) controls the spreading of pigments only in sorghum containing pigmented tests (B1 B2), and dominant S gene (S+) causes the pigments to spread from the testa to the pericarp (Rooney & Waniska, 2000). Sorghums with dominant forms of pigmented tests and spreader genes (B1 B2 S+) have the highest condensed tannin content, and these sorghums are highly resistant to mold and bird attack (Dykes & Rooney, 2006; Rooney & Waniska, 2000).

Therefore, the bran is an important component in sorghum and has a huge influence on the grain appearance and phenolic profile. It is important to note that the bran fraction, especially from black and brown sorghum with high levels of phenolic compounds, is a potential source of functional ingredients for the food and drug industries. Besides, sorghum bran is an industrial by-product and often removed in biofuel production and food and feed processing, and its potential application in foods will be discussed in section
“Incorporating sorghum into other foods.” Understanding the sorghum grain structure, color, and nutritional profile and their relationship with genetics provides new opportunities to breed new sorghum varieties with specific attributes targeting for specific purposes/applications.

**Sorghum Grain Nutritional Profile**

Sorghum nutritional composition varies among varieties. In general, carbohydrates (starch and nonstarch polysaccharides), proteins, and lipids are the main components of the grain (Hill, Lee, & Henry, 2012; Léder, 2004). On average, 100 g of the grain has about 72.1 g carbohydrates, 12.4 g water, 10.6 g proteins, 6.7 g fibers, and 3.5 g lipids, and provides about 1,377 kJ energy (USDA, 2019).

Starch is the dominant carbohydrate in sorghum and is stored as granules in the endosperm. The starch content varies significantly among varieties from 32.1 to 72.5 g per 100 g grain (Udachan, Sahu, & Hend, 2012). Sorghum starch consists of mainly amylose and amylopectin, but some waxy sorghums may not have or have low levels of amylose (Dicko, Gruppen, Zouzouho, et al., 2006). Because of the high levels of resistant starch and slowly digestible starch, and strong interactions among starch granules, endosperm proteins, and condensed tannins, sorghum has the lowest starch digestibility amongst cereal crops (Barros, Awika, & Rooney, 2016; Barros, Awika, & Rooney, 2012). Sorghum is a rich source of fibers as the nonstarch carbohydrate in sorghum is composed of primarily insoluble fibers (75% to 90%) and soluble fibers (10% to 25%), which are found in the pericarp and endosperm cell walls and account for about 6 to 15 g per 100 g of grain (Knudsen & Munck, 1985; Martinol et al., 2012; Taylor & Emmambux, 2010). Sorghum nonstarch carbohydrate is principally constituted of arabinoxylans and β-glucans. The arabinoxylans are essentially gluconorarabinoxylans and contain bound p-coumaric and ferulic acids, important phenolic acids in sorghum (Verbruggen et al., 1998; Verbruggen, Baldman, Voragen, & Hollemans, 1993).

The protein in sorghum can be broadly divided into prolamin proteins (such as kafirins) and non-prolamins proteins (such as globulins, glutelins, and albumins). Kafirins are the principal form of protein storage in sorghum grain and account for 70% of the total protein in sorghum whole grain, whereas the remaining albumins, glutelins, and globulins account for the remainder (Belton, Delgadillo, Halford, & Shewry, 2006; Shewry & Tatham, 1990). There are four types of kafirin based on molecular weight, being α-, β-, γ-, and δ-kafirin, and these proteins are hydrophobic proteins and stored in firmly wrapped protein bodies in the endosperm (Belton et al., 2006; Shewry & Tatham, 1990). Sorghum grain is rich in glutamic acid, proline, and leucine. However, similar to other cereal grains, it may be deficient in lysine, although this problem can be improved by sorghum breeding or food fortification (Belton & Taylor, 2004; Galili & Amir, 2013; Pellett & Ghosh, 2004).

Sorghum proteins have low digestibility. Sorghum kafirins have high degrees of polymerization and extensive disulfide bridges that are resistant to enzymatic digestion in the digestive tract; their strong interaction with tannins and starch also hinders the protein digestion (Belton et al., 2006; Da Silva, Taylor, & Taylor, 2011; Taylor, Bean, Ioerger, & Taylor, 2007). Despite these characteristics, the low starch and protein digestibility makes sorghum a promising food source for people with obesity and diabetes. Sorghum kafirin has been a recent subject of great interest due to its potential across a broad range of applications. Extensive research has been conducted on sorghum kafirin including methods for kafirin extraction, isolation, and modification; kafirin as a gluten-free ingredient in food application such as baking; edible films and coatings derived from kafirin; kafirin microparticles as nutraceuticals and drug carriers. Kafirin is not the focus of this...
Figure 2–Structure of major sorghum phenolic compounds.
Table 1—Sorghum grain classification, genotypes, physical characteristics, and phenolic contents.

<table>
<thead>
<tr>
<th>Sorghum type</th>
<th>Main gene*</th>
<th>Pericarp color</th>
<th>Pigmented testa</th>
<th>Tannins</th>
<th>3-Deoxanthocyanins</th>
<th>Total phenolic contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>yy</td>
<td>White</td>
<td>No</td>
<td>No</td>
<td>Low or absent</td>
<td>Very low</td>
</tr>
<tr>
<td>Yellow</td>
<td>rrY</td>
<td>Yellow</td>
<td>No</td>
<td>No</td>
<td>Low or absent</td>
<td>Low</td>
</tr>
<tr>
<td>Red</td>
<td>R Y and/or</td>
<td>Red</td>
<td>No</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Black</td>
<td>R Y and/or</td>
<td>Red</td>
<td>Yes/No</td>
<td>Varies</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Brown</td>
<td>Bsub Y</td>
<td>Red</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

*Key genes that determine the color and phenolic profile are listed.

review as several reviews have discussed this compound in depth and the reader is directed to these reviews (Belton et al., 2006; De Mesa-Stonestreet, Alavi, & Bean, 2010; Husnain Raza, Muhammad Shoaib, & Sobia Niazi, 2017).

The lipid in sorghum grain is constituted of primarily unsaturated fatty acids, with the polyunsaturated fatty acids being the most abundant. The primary fatty acids in sorghum are oleic, linoleic, palmitic, linolenic, and stearic acids; the lipid profile is similar to that of maize but is more unsaturated (Adeyeaye & Ajewole, 1992; USDA, 2019). Sorghum is also a good source of vitamins and minerals. The vitamin B complex (pyridoxine, riboflavin, and thiamin) and some fat-soluble vitamins (vitamins A, D, E, and K) are the principal vitamins in sorghum, with potassium, phosphorus, magnesium, and zinc being the main minerals (Léder, 2004; Martinol et al., 2012; USDA, 2019). The high levels of resistant starch, fibers, relatively low-digestibility proteins (kafirins), and unsaturated fatty acids award sorghum with unique nutritional attributes and functional health benefits.

Sorghum Grain Bioactive Phenolic Compounds

In sorghum, the bioactive compounds are primarily the phenolic compounds. The main phenolic compounds include phenolic acids, flavonoids, condensed tannins, stilbenes, and lignins, which are produced by the phenylpropanoid pathway. Sorghum grain contains a unique phenolic profile due to the high proportion of the phenolic acids, flavonoids (3-deoxyanthocyanidins), and condensed tannins, which are the focus of this review. The structure and profile of the main phenolic compounds in sorghum are summarized in Figure 2 and Table 2, respectively.

Phenolic acids

Phenolic acids (Table 2) are the most simple but abundant phenolic compounds that are present in all sorghum grain, with a total concentration of 445 to 2,850 µg/g (Girard & Awika, 2018). According to their structure, the phenolic acids can be divided into two categories: benzoic and cinnamic acid (Figure 2). The main phenolic acids reported in sorghum grain are gallic, vanillic, protocatechuic, cinnamic, p-coumaric, p-hydroxybenzoic, syringic, ferulic, caffeic, and sinapic acids (Althwab, Carr, Weller, Dweikat, & Schlegel, 2015; Vanamala, Massey, Pinnamaneni, Reddivari, & Recdron, 2018).

The phenolic acids are present in the endosperm, pericarp, and testa of the grain, and exist in both free and bound forms. The free phenolic acids, which are extractable by organic solvents, are not bound to the cell wall, and are mostly found in the pericarp and testa. They are often conjugated with monomeric carbohydrate and glycerol and exist in the free form as esters (conjugated) or aldehydes (unconjugated). The ester conjugates are the primary extractable phenolic acids in sorghum (Dykes & Rooney, 2006; Svensson, Sekwati-Monang, Lutz, Schieber, & Gänzle, 2010; Yang, Allred, Geera, Allred, & Awika, 2012).

However, the bound phenolic acids are attached to the cell wall (lignin) via covalent bonds and are also part of the cell wall structure, and the extraction requires acidic or alkaline conditions and high temperature to break the covalent bonds (Wu et al., 2017). Most of the phenolic acids (about 70% to 95%) in sorghum are in the bound form. Among them, ferulic acid (100 to 500 µg/g in the grain) is the most abundant one and can account for up to 90% of the total bound phenolic acids (Chiremba, Taylor, Rooney, & Beta, 2012; Yang et al., 2012). The bound phenolic acids have low bioavailability, because of the extensive covalent bonds that are resistant to enzymatic digestion (Saura-Calixto, 2010). Moreover, because the bound phenolic acids are part of cell wall components, the concentration of bound phenolic acids is also directly linked to the grain hardness, with higher concentrations being associated with harder grain (Chiremba et al., 2012).

Flavonoids

Flavonoids are mainly found in sorghum bran, and the types and concentrations are associated with the pericarp color and thickness and presence of pigmented testa (Awika et al., 2005; Dykes et al., 2005). They are the largest class of phenolic compounds in plants and represent the most abundant and diverse phenolic compounds in sorghum. Flavonoids share the basic flavan skeleton (Figure 2C) and their classification is based on the presence of C2–C3 double bond and substituent groups on the C-ring (Buer, Imam, & Djordjević, 2010). A wide class of flavonoids (Table 2) have been found in sorghum including anthocyanins (3-deoxanthocyanidins), flavones, flavonanes, flavan-3-ols, flavan-4-ols, flavonols, and dihydroflavonols (Awika, 2017; de Morais Cardoso et al., 2017). Among the flavonoids, 3-deoxanthocyanidins, flavones, and flavanonones are the dominant compounds in sorghum.

Flavones. Flavones are yellow-colored flavonoids commonly found in fruits, vegetables, legumes, and also in cereal grains. Although cereal grains generally contain modest levels of flavones, they represent one of the main dietary sources of the flavones and thus play a significant role in the human diet (Zamora-Ros et al., 2016). The flavone content (Figure 2D; Table 2) in sorghum grain is about 20 to 390 µg/g, relatively low compared to other flavonoids (Girard & Awika, 2018). Some flavonoids exist naturally in the form of glycosides such as luteolin, but others like apigenin exist mainly as aglycone forms (Yang et al., 2012; Yang, Allred, Dykes, Allred, & Awika, 2015). The glycosides in sorghum are predominant O-glycosides and are very unstable in acidic environments, because the glycosidic bonds are readily hydrolyzable and form the aglycones; the aglycone forms of luteolin and apigenin are the dominant flavones in sorghum (Dykes et al., 2011; Yang et al., 2015). Generally, both luteolin and apigenin are the dominant flavones in sorghum; however, in other cereal grains, the flavones exist mainly as apigenin and in the glycoside (C-glycosides) form (Dykes & Rooney, 2007; Dykes et al., 2011; Dykes et al., 2009). The O-glycosides are more bioaccessible than C-glycosides due to the readily hydrolyzable property in acidic stomach environment, and thus have high bioactivity at low concentrations (Yang et al., 2015; Zamora-Ros et al., 2016). Therefore, sorghum flavones are more abundant than other cereals with
Table 2—Major phenolic compounds (free or bound form) identified in sorghum (bran or whole grain fraction) (µg/g).

<table>
<thead>
<tr>
<th>Class</th>
<th>Main compounds</th>
<th>Free</th>
<th>Bound</th>
<th>Bran</th>
<th>Grain/Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenolic acids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallic acid</td>
<td>15 to 1,650 (2018 R)</td>
<td>430 to 1,200 (2018 R)</td>
<td>N/A</td>
<td>445 to 2,850 (2018 R)</td>
<td></td>
</tr>
<tr>
<td>Protocatechuic acid</td>
<td>6.3 to 13 (1983)</td>
<td>11.5 to 218.3 (1983)</td>
<td>N/A</td>
<td>150.3 to 176.2 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Vanillic acid</td>
<td>0 to 126.7 (1983)</td>
<td>0 to 65.6 (1983)</td>
<td>N/A</td>
<td>15.4 to 23.4 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Syringic acid</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>15.7 to 17.5 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Cinnamic acids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferulic acid</td>
<td>8.7 to 74 (1983)</td>
<td>91.9 to 297.2 (1983)</td>
<td>1,400 to 2,170 (1984)</td>
<td>120.5 to 173.5 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Sinapic acid</td>
<td>N/A</td>
<td>N/A</td>
<td>100 to 630 (1984)</td>
<td>50 to 140 (1983)</td>
<td></td>
</tr>
<tr>
<td>p-Coumaric acid</td>
<td>6.4 to 109.1 (1983)</td>
<td>38 to 138.5 (1983)</td>
<td>103 to 396 (2012 R)</td>
<td>41.9 to 71.9 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Cinnamic acid</td>
<td>0 to 10.7 (1983)</td>
<td>0 to 19.7 (1983)</td>
<td>0 to 970 (1984)</td>
<td>70 to 230 (1983)</td>
<td></td>
</tr>
<tr>
<td>Flavonoids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flavones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apigenin</td>
<td>0 to 6.7 (Wu)</td>
<td>0 to 23.14 (Wu)</td>
<td>N/A</td>
<td>4.9 to 15.0 (2017 R)</td>
<td></td>
</tr>
<tr>
<td>Luteolin</td>
<td>0.38 to 19.74 (Wu)</td>
<td>0 to 19.39 (Wu)</td>
<td>N/A</td>
<td>20 to 390 (2018 R)</td>
<td></td>
</tr>
<tr>
<td>Naringenin</td>
<td>1.15 to 31.88 (Wu)</td>
<td>0 to 20.58 (Wu)</td>
<td>N/A</td>
<td>0 to 2,000 (2018 R)</td>
<td></td>
</tr>
<tr>
<td>Eriodictyol</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0 to 1,504 (2011)</td>
<td></td>
</tr>
<tr>
<td>(continued)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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### Table 2—Continued.

<table>
<thead>
<tr>
<th>Class</th>
<th>Main compounds</th>
<th>Free</th>
<th>Bound</th>
<th>Grain/Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Deoxyanthocyanidins</td>
<td>Apigeninidin</td>
<td>0 to 23.24 (Wu)</td>
<td>0 to 23.84 (Wu)</td>
<td>1,600 to 6,100 (2004)</td>
</tr>
<tr>
<td></td>
<td>Luteolinidin</td>
<td>0.04 to 18.25 (Wu)</td>
<td>0.30 to 11.72 (Wu)</td>
<td>Trace to 1,800 (2004)</td>
</tr>
<tr>
<td>7-Methoxyapigeninidin</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>5-Methoxyluteolinidin</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Condensed tannins (Proanthocyanidins)</td>
<td>Catechin</td>
<td>N/A</td>
<td>N/A</td>
<td>330 Sumac (2003)</td>
</tr>
<tr>
<td>Monomeric</td>
<td>Procyanidin B1</td>
<td>N/A</td>
<td>N/A</td>
<td>1,330 Sumac (2003)</td>
</tr>
<tr>
<td>Dimeric</td>
<td>Procyanidin</td>
<td>N/A</td>
<td>N/A</td>
<td>58,440 Sumac (2003)</td>
</tr>
<tr>
<td>Polymeric</td>
<td>Proapigeninidin</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Proluteolinidin</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

All results in the table are obtained from HPLC method and quantified using authentic standards only, and the significant different values from different studies may due to the differences in sorghum genotype and growth conditions, and inconsistency of the extraction and determination method. Sumac = sumac (brown) sorghum bran; White = white sorghums; Red = red sorghums; Black = black sorghums. N/A = not available or not quantified. References: 1983 = Hahn, Faubion, and Rooney (1983); 1984 = Hahn (1984); 2003 = Awika, Dykes, Gu, Rooney, and Prior (2003); 2004 = Awika et al. (2004); 2005 = Awika et al. (2005); 2005 D = Dicko, Gruppen, Traoré, van Berkel, and Voragen (2005); 2009 = Dykes et al. (2009); 2011 = Dykes et al. (2011); 2012 = Taleon et al. (2012); 2012 B = Bound phenolics from sorghum bran from Chiremba et al. (2012); 2013 = Dykes et al. (2013); 2014 = Taleon, Dykes, Rooney, and Rooney (2014); Wu = Wu et al. (2017); Wu, Johnson, Bonman, Bennett, and Fang (2017); and Wu et al. (2018); 2017 R = Reviewed by de Morais Cardoso et al. (2017); 2018 R = Reviewed by Girard and Awika (2018).
higher bioavailability. Sorghum varieties with red and yellow pericarp are often reported to have high levels of flavones (Dykes et al., 2011; Dykes et al., 2009).

**Flavanones.** Flavanones are widely distributed in food plants with naringenin and its derivatives being the dominant ones. They are the main intermediates in the biosynthesis of flavonoids, but their presence in cereal grains is generally rare (Awika, 2017; Koes, Quattrocchio, & Mol, 1994). Sorghum appears to be an exception, and some sorghum varieties have been reported to have the highest levels of flavanones among food plants (Awika, 2017). The flavanone content (Figure 2E; Table 2) in sorghum ranges from 0 to 2,000 µg/g. The lowest level is reported in white sorghum, and the highest level is found in sorghum with a yellow pericarp (Bhagwat, Haytowitz, & Holden, 2014; Dykes et al., 2011; Yang et al., 2015). Naringenin and eriodictyol glycosides are the main flavanones in sorghum, whereas their aglycones and O-methylated derivatives are relatively limited (Guger, Magnolato, & Self, 1986; Yang et al., 2015; Yang et al., 2012). Similar to the flavones, the glycosides of flavanones are mainly the O-glycosides, which are sensitive to low pH, easily hydrolyzable, and have high bioavailability (Yang et al., 2015).

**3-Deoxyanthocyanidins.** The unique feature of sorghum flavonoids is its anthocyanin content. Anthocyanins are a class of natural water-soluble pigments and antioxidants (Riaż, Zia-Ul-Haq, & Saad, 2016). The majority of natural anthocyanins in plants are C-3-hydroxylated anthocyanins; however, the anthocyanins found in sorghum are almost exclusively the C-3-deoxylated analogs, that is, 3-deoxyanthocyanidins (Figure 2F), which are a rare subclass of anthocyanins (Awika, Rooney, & Waniska, 2004; Xiong, Zhang, Warner, & Fang, 2019). Both 3-deoxyanthocyanidins and anthocyanins are derived from the flavonone biosynthetic pathway but are divergent from flavonone intermediates (that is, naringenin; Kawabagashi et al., 2016; Liu et al., 2010). The main difference between 3-deoxyanthocyanidins and anthocyanins is the lack of an OH group in the position C-3, and this structural difference renders 3-deoxyanthocyanidins with unique chemical properties (Awika et al., 2004).

The main 3-deoxyanthocyanidins (Figure 2F; Table 2) in sorghum are apigeninidin and luteolinidin aglycones. Their derivatives including the methoxylated form (7-methoxy-apigeninidin, 7-methoxy-luteolinidin, and 5-methoxy-luteolinidin), glycosides (apigeninidin 5-glucoside and luteolinidin 5-glucoside), and methoxylated glycosides (7-methoxy-apigeninidin 5-glucoside, 7-methoxy-luteolinidin 5-glucoside, and 5-methoxy-luteolinidin 7-glucoside) are also reported and in relatively moderate or small quantities (Dykes et al., 2013; Dykes et al., 2009; Petti et al., 2014; Wu & Prior, 2005). Moreover, other novel derivatives such as dimeric 3-deoxyanthocyanidins (for example, apigeninidin-flavone dimer) and pyranic 3-deoxyanthocyanidins (an additional ring connected to the C-4 and C-5 position) have also been reported and demonstrated promising color stability (Bai et al., 2014; Geera, Ojwang, & Awika, 2012; Khalil, Baltenweck-Guyot, Ocampo-Torres, & Albrecht, 2010).

3-Deoxyanthocyanidins are one of the most abundant flavonoids in sorghum, with a total concentration of 200 to 4,500 µg/g (Table 2); in some sorghums, the 3-deoxyanthocyanidin content can account for up to 80% of the total flavonoids in the grain (de Morais Cardoso et al., 2017; Girard & Awika, 2018). 3-Deoxyanthocyanidins are concentrated in the bran layer of the grain, up to four to five times higher than in the whole grain, and sorghum with a red pericarp genotype (B_Y+) is particularly rich in 3-deoxyanthocyanidins (Awika et al., 2005; Awika et al., 2004; Awika, Rooney, & Waniska, 2005). Among the red pericarp sorghum genotypes, black sorghum (genotypically red but phenotypically black) bran has the highest levels of 3-deoxyanthocyanidins (1,790 to 6,120 µg/g), at least twice higher than red (both genotypically and phenotypically red) and brown sorghum (red genotype with pigmented testa) bran (Table 1) (Awika et al., 2005; Dykes et al., 2005; Dykes et al., 2013; Dykes et al., 2009). In addition, 3-deoxyanthocyanidins are also distributed in other plant tissues of sorghum such as the sheath and leaves, with a concentration up to 90,000 µg/g (Geera et al., 2012; Petti et al., 2014).

Apart from providing attractive orange/red to blue/violet colors to plants, 3-deoxyanthocyanidins are potent antioxidants with antimicrobial activity and many other benefits (Yang et al., 2019). Sorghum is considered as the main dietary source for 3-deoxyanthocyanidins for humans, which could be exploited as commercial natural colorants for foods as discussed in section “The potential application of sorghum phenolic compounds.”

**Condensed tannins**

Tannins have been one of the most investigated polyphenols in sorghum. In nature, they are widely distributed in plants, such as grapes, tea, and legumes, as monomers or low molecular weight oligomers (Ojwang, Yang, Dykes, & Awika, 1992). However, sorghum tannins (condensed tannins or proanthocyanidins) are in the condensed form with high molecular weight and a high degree of polymerization (DP), which are not commonly found among the major cereals (Wu et al., 2012). Sorghum condensed tannins (Figure 2G; Table 2) are composed of oligomers or polymers of mainly flavan-3-ol and flavan-3,4-diols and connected primarily by B-type linkages, with an average DP of about 20 compared to other tannin-containing cereal grains of 3 to 10 DP (Dykes & Rooney, 2006; Girard & Awika, 2018). The low molecular weight forms such as monomers (mainly catechin and dimers (mainly procyandin B1) are present in small quantities in sorghum grain (Awika & Rooney, 2004).

The tannin content in sorghums varies significantly among varieties. Based on the genotype and tannin concentration and extractability, sorghums can also be classified into three types (Table 3). Type I sorghums have recessive B1 and/or B2 gene (B1b_b2b2, B1b_B2_a or B1b_B2_b2) and have no pigmented tests, and thus have no or very low levels of tannins (0 to 1.8 mg CAE/g). Type II sorghums have dominant B1 and B2 but homozgyous recessive S gene (B1_b2_aS) and have pigmented tests with moderate levels of tannins (6.4 to 15.5 mg CAE/g); the tannins are mainly located in the vesicles within the testa and are extractable with acidified methanol. Type III sorghums have pigmented tests, all B1, B2 and S genes are being dominant (B1_b2_aS), with high levels of tannins (11 to 50.2 mg CAE/g); the tannins are mainly found in the testa cell walls as well as the pericarp, and are extractable by methanol or acidified methanol (Dykes & Rooney, 2006; Earp et al., 2004; Rooney, Murty, & Mertin, 1982).

In general, sorghums with pigmented tests have high levels of condensed tannin content, and type III sorghums are among the highest with the concentration more than 10 times higher than other tannin-containing cereals (Dykes et al., 2013; Girard & Awika, 2018). Sorghums with high tannin content have agronomical advantages of protecting the plant against pathogens and birds and have been commonly grown in some under-developed regions with a food security problem (Bullard, Garrison, Kilburn, & York, 1980; Kil et al., 2009; Taylor, 2003).
Phenolic compounds are naturally produced in sorghum and play an important role in plant defense against pathogens and pests. As food components, their health benefits to human have been widely investigated. Phenolic acids, flavonoids, and condensed tannins are the main phenolic compounds in sorghum with relatively high concentrations (Table 2), providing an excellent source for human intakes. Besides, different sorghum varieties have a very different phenolic profile and thus could be used for various purposes.

### Potential Health Benefits of Sorghum Grain

#### Antioxidant activity

Oxidative stress, which is an imbalance of free radicals and antioxidants, is the leading cause of various chronic diseases (Lee, Park, Zuidema, Hannink, & Zhang, 2011). The antioxidant activity of sorghum phenolic compounds seems to play a key role in the health promotion and disease prevention associated with sorghum consumption. Various methods have been used to measure the antioxidant activity of natural compounds, and these methods are almost exclusively based on the colorimetric methods using *in vitro* assays. Oxygen radical absorbance capacity (ORAC), ferric reducing antioxidant power, and 2,2′-azino-bis(3-ethylbenzthiazoline-6-sulfonic acid) (ABTS) and 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical scavenging methods are the current widely used *in vitro* methods for estimation of sorghum antioxidant activity. The phenolic compounds extracted from sorghum grain exhibit the highest antioxidant activity among cereal grains of wheat, rice, and corn, and are also comparable to common fruits and vegetables (Adom & Liu, 2002; Awika, Rooney, Wu, Prior, & Cineros-Zevallos, 2003b; Miller, Rigelhof, Marquart, Prakash, & Kanter, 2000; Wu et al., 2004).

The antioxidant activity is strongly related to the total phenolic contents, particularly the condensed tannin content in sorghum (Awika et al., 2003b). Sorghums with condensed tannins (black and brown sorghums) have consistently demonstrated high antioxidant *in vitro*, especially in the bran where the phenolics are concentrated (Awika et al., 2005; Dykes et al., 2005). For example, a brown sorghum (Sumac SU99) bran showed the highest *in vitro* antioxidant activity (ORAC = 3,124 μmol TE/g, ABTS = 768 μmol TE/g, and DPPH 716 μmol TE/g) among sorghum (grain or bran), and higher than most of fruits and vegetables known to have high antioxidant activities including blueberry (ORAC = 842 μmol TE/g), strawberry (ORAC = 402 μmol TE/g), and broccoli (173 μmol TE/g) (Awika et al., 2003b; Wu et al., 2004).

However, it is important to note that the *in vitro* antioxidant activity does not accurately, or does not at all, reflect the actual antioxidant capacity or health benefits *in vivo*, because it does not account for the physiological conditions such as pH, temperature, bioavailability, and metabolism (Granato et al., 2018; Liu & Finley, 2005). Biological systems are far more complicated than the simple *in vitro* assays used, and antioxidants may function through multiple steps and mechanisms (Wolfe & Liu, 2007). The best approach to examine the antioxidant activity may involve animal or human subjects, but this is more expensive, time-consuming, and perhaps risky. Wolfe and Liu (2007) developed a method to quantify the antioxidant activity using cell culture, and this cellular method has recently gained increasing popularity because it is cost-effective, relatively fast, and most importantly, takes into account the biological system, and more accurately reflects the antioxidant activity. Recently, Wu et al. (2018) applied this method to investigate the cellular antioxidant activity in sorghum-incorporated Chinese steamed bread, and showed that incorporation of sorghum in the bread significantly increased the cellular antioxidant activity. However, the “actual” antioxidant activity of sorghum phenolic compounds still requires further investigation.

Apart from the direct antioxidant effects, the phenolic compounds from sorghum have been shown to induce endogenous detoxifying enzymes (phase II enzymes) that are responsible for converting the harmful reactive oxygen or nitrogen species into nontoxic compounds, and thus indirectly enhances the body defense against oxidative stress (Awika, Yang, Browning, & Faraj, 2009; González-Montilla et al., 2012; Yang et al., 2009).

Among sorghum phenolic compounds, 3-deoxyanthocyanidins have shown a strong influence on the phase II enzyme activity, specifically, the enzyme NADH:quinone oxireductase (NQO) activity. 3-Deoxyanthocyanidins are strong NQO inducers; both 3-deoxyanthocyanidin standards and 3-deoxyanthocyanidin-rich sorghum extract were reported to significantly increase the NQO activity in some cancer cells (Awika et al., 2009; González-Montilla et al., 2012; Yang et al., 2009), and such effect has not been reported in their anthocyanin analogs. The inducing capacity of 3-deoxyanthocyanidins on the phase II enzyme varies greatly with their structure and substitution. Methoxylated substitution at the C-5 and C-7 positions, such as 7-methoxyapigeninidin and 5,7-dimethoxyapigeninidin, can significantly enhance the inducing effect on the NQO activity (Awika et al., 2009; Yang et al., 2009).

Black and red sorghums that are rich in 3-deoxyanthocyanidins have strong inducing effects on the NQO activity. Surprisingly, sorghums with white pericarp and low 3-deoxyanthocyanidin content have also been reported to show significant inducing effects on the NQO; other bioactive compounds may also have involved, which requires further investigation (Awika et al., 2009; Yang et al., 2009). Notwithstanding, sorghum 3-deoxyanthocyanidins play an important role in combating oxidative stress. In addition, it should be mentioned that among the sorghum phenolics, sorghum condensed tannins are the most powerful antioxidants *in vitro* and may be directly linked to the antioxidant activity *in vivo* (Awika et al., 2005; Hagerman et al., 1998). Because condensed tannins are not absorbable by the body and also react with other molecules to form complexes, they may act as free radical “sinks,” especially in the gastrointestinal tract, against the oxidative stress (Tian et al., 2012).
**Anti-inflammatory activity**

Long-term oxidative stress can lead to chronic inflammation and consequently can result in various chronic diseases. During inflammation, a number of pro-inflammatory compounds such as interleukin (IL), cyclooxygenase (COX)-2, tumor necrosis factor (TNF-α), and prostaglandin E2 (PG-E2) are generated (Shim, Kim, Jang, Ko, & Kim, 2013). Many phenolic compounds from sorghum grain have been demonstrated to inhibit the production of these pro-inflammatory compounds (Burdette, 2007; Funakoshi-Tago, Nakamura, Tago, Mashino, & Kasahara, 2011; Makanjuola, Ogundaini, Ajonuma, & Dosunmu, 2018; Shim et al., 2013; Wölffe et al., 2011). For example, phenolic acids, such as gallic acid and ferulic acids, were reported to suppress the COX-2 enzyme, and ferulic acid has been shown to inhibit the production of TNF-α (Burdette, 2007). Flavone apigenin and luteolin were reported to inhibit the production of COX-2, and inhibit the transcription factor (nuclear factor kappa B) that activates the production of these pro-inflammatory compounds (Agah, Kim, Mertens-Talcott, & Awika, 2017; Burdette, 2007; Funakoshi-Tago et al., 2011; Wölffe et al., 2011). 3-Deoxyanthocyanidins have also been shown to suppress the production of COX-2 and PG-E2 (Makanjuola et al., 2018). The inhibitory effects against the pro-inflammatory compounds is believed to be important for disease prevention. In addition, recent studies have shown that the combination of flavon apigenin and flavonol quercetin, as well as the apigenin-rich extract from sorghum and quercetin-rich extract from cowpea, has a strong synergistic anti-inflammatory effect by enhancing their bioavailability through the suppression of the phase II metabolism and ATP binding cassette membrane transporter function in cellular models (Agah et al., 2017; Ravisankar et al., 2019). It has been suggested that the C2 = C3 conjugation structure of apigenin and quercetin may play an important role in enhancing the anti-inflammatory effect (Ravisankar et al., 2019).

Furthermore, the crude phenolic extract from sorghum bran, especially from black sorghum, has demonstrated strong inhibitory effects against COX-2, IL-1β, and TNF-α pro-inflammatory activity, and the effect is similar to the anti-inflammatory drug indomethacin (Burdette et al., 2010; Shim et al., 2013). Also, mice with inflammatory triggered ear edema treated with the phenolic extract from black and red sorghum bran demonstrated significant reduction of ear edema (Burdette et al., 2010), and the same effect was also shown in mice when consuming the whole grain of sorghum (Shim et al., 2013). Recently, a study showed that the introduction of sorghum whole grain biscuits in the human (overweight adults) diet significantly reduced the pro-inflammatory compounds IL-1β, IL-6, IL-8, and TNF-α over 12 weeks (Stefoska-Needham et al., 2017). Moreover, the phenolic extract from sorghum bran has also been shown to inhibit hyaluronidase enzyme, an enzyme that is involved in chronic joint inflammation; all sorghum varieties, regardless of pericarp color and condensed tannin content, demonstrated a significant inhibitory effect against hyaluronidase activity (Bralley, Greenspan, Hargrove, & Hartle, 2008).

**Cancer prevention**

The phenolic compounds from sorghum have shown anticancer activity, and consumption of sorghum whole grain can reduce the risk of developing certain cancers (Chen, Cole, Mi, & Xing, 1993; Issacson, 2005). The anticancer activity of sorghum may be attributed to the potent antioxidant activity and phase II enzyme induction of its phenolic compounds (Awika et al., 2009).

Among the sorghum phenolic compounds, 3-deoxyanthocyanidins have received the most attention. Both 3-deoxyanthocyanidins and 3-deoxyanthocyanidin-rich sorghum extract have been demonstrated to be effective against the growth of various cancer cells, including colon, hepatoma, esophageal, intestinal epithelial, leukemia, breast, and stomach cancer cells; these compounds act directly against cancer by inducing cell apoptosis and inhibiting the proliferation and metastasis of cancer cells (Awika et al., 2009; Devi, Saravanakumar, & Moh, 2011; Massey, Reddivari, & Vanamala, 2014; Shih et al., 2007; Suganyadevi, Saravanakumar, & Mohandas, 2013; Woo et al., 2012; Yang et al., 2009). It should be noted that 3-deoxyanthocyanidins are more effective than their anthocyanidin analogs on this property. For instance, apigeninidin and luteolinidin were reported to be more cytotoxic than their anthocyanin analog pelargonidin and cyanidin, respectively, to human intestinal epithelial (HEP-G2) and leukemia (HL-60) cancer cells (Shih et al., 2007).

Sorghum condensed tannin may also play an important role in cancer prevention. Sorghum tannins have been shown to inhibit aromatase (an enzyme that is involved in breast cancer) and thus prevent the formation of undesirable cancer growth stimulus (Hargrove, Greenspan, Hartle, & Dowd, 2011; Huang, Cai, & Zhang, 2009). The tannin-rich extract from brown sorghum bran was reported to inhibit aromatase activity at low concentrations, and much more strongly than the 3-deoxyanthocyanidin-rich, but tannin-free, extract from black sorghum bran (Hargrove et al., 2011), which suggests that condensed tannins may have more potent anticancer activity than 3-deoxyanthocyanidins. Tannins extracted from sorghum were also reported to be more effective against the growth of colon cancer cells than tannins from grape seed (Awika, 2011). Furthermore, other sorghum phenolic compounds such as flavones and flavanones have also demonstrated anticancer activity, especially the flavone apigenin, which was reported to activate estrogenic activity and induce apoptosis of the colon cancer cells (Yang et al., 2015; Yang et al., 2012).

**Antidiabetes and obesity prevention**

Sorghum whole grain is an excellent food for people with obesity and diabetes. Sorghum has a relatively low starch digestibility. As explained previously, this is because sorghum endosperm contains high levels of resistant and slowly digestible starch (Barros et al., 2012; Taylor & Emmambux, 2010). During hydrothermal food processing, extensive cross-linking are formed between sorghum protein (kafrin) and starch, and the cross-linking is mainly composed of the strong disulfide bonds that are resistant to digestion (Duodu, Taylor, Belton, & Hanaker, 2003; Ezeogo, Duodu, Emmambux, & Taylor, 2008). Additionally, sorghum condensed tannins can react with starch and proteins to form bulk complexes in the gastrointestinal tract, which makes them even less digestible or nondigestible (Amaoko & Awika, 2019; Barros et al., 2012; Taylor & Emmambux, 2010). Sorghum condensed tannins have much stronger complexation with starch than simple phenolic compounds, and the higher molecular weight of tannin the stronger the interaction with starch (Barros et al., 2012). These complexes can provide satiety and reduce caloric intake, and also produce a low glycemic response that is desirable for people with obesity and diabetes (Zhang & Hamaker, 2009). A recent study showed that healthy people who consumed biscuits made of sorghum whole grain reported higher satiety and lower hunger ratings than wheat biscuits (Stefoska-Needham, Beck, Johnson, Chu, & Tapsell, 2016).
Sorghum also has potential antidiabetic activities. The phenolic extract from sorghum grain has been demonstrated to have inhibitory activity against digestion enzymes such as Bacillus stearothermophilus α-glucosidase, porcine pancreatic α-amylase, and human salivary α-amylase, therefore reducing the glycemic level. Some sorghums have even shown more robust α-glucosidase inhibitory activities than the common antidiabetic drug acarbose (Kim, Hyun, & Kim, 2011). Administration of sorghum phenolic extract to streptozotocin-induced diabetic rats has been shown to significantly decrease the plasma glucose concentration in these rats and was as effective as the antidiabetic drug glibenclamide (Chung, Kim, et al., 2011; Kim & Park, 2012). The phenolic extract was also reported to increase the serum insulin concentration in these rats (Chung, Kim, et al., 2011). Sorghum phenolics may play a role in insulin regulation and act as an adjuvant in diabetic treatment (Chung, Kim, et al., 2011). Moreover, consumption of muffins with the incorporation of sorghum has been shown to influence the blood glucose and insulin levels, and improve the glycemic response in healthy people (Poquette, Gu, & Lee, 2014).

The antidiabetic activity of sorghum may be partially attributed to the condensed tannins. A study has shown that the tannin-rich extract from brown sorghum bran extracts inhibitory activities against porcine pancreatic α-amylase at low concentrations (Hargrove et al., 2011). More recently, Links, Taylor, Kruger, and Taylor (2015) have demonstrated that the crude extract from a type III tannin sorghum had powerful inhibitory activities against yeast α-glucosidase, which was about 20,000 times stronger than acarbose, although acarbose was better at inhibiting the porcine pancreatic α-amylase. These enzymatic activities are effectively inhibited by sorghum phenolics, especially in sorghum with high tannin content. The inhibition of digestive enzymes, to prevent glucose digestion, may be the first step in antidiabetic mechanism (Links et al., 2015). Incorporating sorghum into the mainstream diet could help to prevent obesity and diabetes and improve human health status.

Dyslipidemia and cardiovascular disease prevention

As discussed above, sorghum grain contains diverse bioactive phenolic compounds, and these compounds may also provide protection against the risk of dyslipidemia and cardiovascular disease. Sorghum lipids of phytosterols and polycosanols have been shown to promote cardiovascular health by regulating the absorption, excretion, and synthesis of cholesterol. For example, incorporation of sorghum lipids into the diet of hamsters increased the excretion of cholesterol and its metabolites, and thus reduced the plasma and liver cholesterol levels in hamsters (Carr et al., 2005; Hoi et al., 2009). These lipids have also been shown to influence the gut microbiota in hamsters, such as reducing the Clostridium species family, to reduce the cholesterol absorption (Martinez et al., 2009). Sorghum phenolic compounds may also play a role in cholesterol metabolism. Studies have shown that the administration of sorghum phenolic extract significantly lowered the plasma cholesterol and triacylglycerol levels in hyperlipidemic or diabetic rats (Chung, Kim, et al., 2011; Chung, Yeo, et al., 2011; Kim & Park, 2012).

Therefore, both whole sorghum grain/ingredients and extracted sorghum phenolic compounds have been demonstrated to have positive health effects. These benefits are mainly derived from the antioxidant effects of phenolic compounds, which can prevent a series of negative oxidative chain reactions, as well as reducing food digestion by its slowly digestible starch and proteins and their complexation with the phenolic compounds. Currently, researchers are trying to uncover the mechanisms behind the health effects, whereas others are attempting to develop novel food products using sorghum as discussed below.

Application of Sorghum Grain in the Food System

Traditional application in the food system

For centuries, sorghum has been a staple food feeding millions of people globally and is particularly important in some underdeveloped regions of Asia and Africa. Sorghum has been traditionally used to make various foods. The traditional food application of sorghum can be broadly categorized into five groups: steamed products, boiled products, baked foods, deep-fried products, and fermented alcoholic beverages.

Steamed products, that is, sorghum couscous, a dish of small balls made of steamed sorghum grain granules (often blended with other grains), similar to those prepared from wheat and millet, is the main staple food in North Africa (Dicko, Gruppen, Traoré, Voragen, & Van Berkel, 2006). Boiled products, such as sorghum porridge and soup, are widely consumed in Africa. Sorghum porridge is made of sorghum whole grains (often mixed with other grains such as maize and millet), with or without fermentation. For example, Ogi, a thin and fermented porridge, has been an important weaning food for babies in Africa (Anglani, 1998). Baked foods such as flatbread (Tortillas) and pancake (Roti) are made from sorghum flour (often in blends with maize) and baked as flat and unleavened (without fermentation) bread or pancake. They are the leading staple food in some regions of Asia and Africa. Because sorghum protein lacks gluten, the dough is unable to form a network to hold gas, and thus the baked sorghum products often have low volume, lack of elasticity, and dark color. Despite this, these products are still preferred by many people (Anglani, 1998; Léder, 2004). The deep-fried sorghum products such as Tortilla chips and Jowar crunch, which are made from sorghum whole grain or sorghum dough, are popular in Asia and Africa (Serna Saldivar et al., 1988; Vivas-Rodriguez, Serna-Saldivar, Waniska, & Rooney, 1990). In addition, sorghum has been traditionally used in home-made alcoholic beverages. In East Asia, red sorghum has been an important ingredient in making high-alcohol spirits such as Chinese Gaoliang and Maotai spirits. In Africa, white and red sorghum have been traditionally used to produce opaque low-alcohol beers; especially in Nigeria, sorghum has been used to produce beers such as lager and stout on a large industrial scale. These beers are gluten free and have a pleasant fruity flavor and have achieved a huge commercial success (Ilori, Makina, & Irefin, 1996; Kayodé, Hounhouigan, Nout, & Niehof, 2007).

Nowadays, due to the growing consumer awareness of the importance of healthy eating, there has been an increased demand for foods or ingredients with healthy and functional properties. Sorghum has recently attracted much attention due to its high nutritional value, and abundant and diverse phenolic compounds as discussed above. Table 4 summarized the key applications and developments of sorghum or sorghum ingredients in the food system, especially in the past 10 years.

Sorghum grain as functional foods and beverages

Development of new, functional, and healthy foods and beverages has been one of the recent core innovations of the food industry, and various sorghum foods have been made and investigated (Table 4). Unlike other major gluten-containing cereal crops such as wheat and barley, sorghum is considered to be gluten free and is a promising and safe alternative food source for people with celiac diseases. No symptom of gastrointestinal distress was observed for
### Table 4—Selective applications of sorghum in the food system since 2009.

<table>
<thead>
<tr>
<th>Applications</th>
<th>Food types</th>
<th>Sorghum components / ingredients</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
</table>
| Sorghum fooda              | Cookies                             | Decorticated tannin (R) and nontannin (W, R) sorghum grain flour          | • Tannin sorghum cookies had high PC and AA, but low sensory acceptance  
• Tannin-free sorghum cookies had low PC and AA, but high sensory acceptance  
• Higher satiety than wheat biscuit  
• Could improve glycemic response  
• Could improve glycemic response  
• Reduced oxidative stress and inflammation  
• But not different from wheat biscuit regarding the health function in overweighted people | Chiremba et al., 2009  
Stefoska-Needham et al., 2016  
Stefoska-Needham et al., 2017  
Liu et al., 2012  
Wolter et al., 2014  
Mkandawire et al., 2015  
Anunciacao et al., 2017  
Lopes et al., 2018  
Cisse et al., 2018  
Wu et al., 2013  
Xiong et al., 2019  
Queiroz et al., 2018  
Garzón et al., 2019 |
| Flaked biscuit             | Cookies                             | Whole grain                                                               | • Sorghum noodle was different from wheat noodle in physical quality  
• Manufacturing sorghum noodles with good physical attributes is possible by controlling the flour quality  
• Sorghum cereal had higher PC, AA, and sensory acceptance, but less vitamin E than wheat cereal  
• Rich source of dietary fiber and PC and AA | Liu et al., 2012  
Mkandawire et al., 2015  
Lopes et al., 2018  
Cisse et al., 2018  
Queiroz et al., 2018  
Garzón et al., 2019 |
| Functional staple foods    | Chinese egg noodles                 | Decorticated, nontannin sorghum grain flour (W, R)                        | • Sorghum noodle was different from wheat noodle in physical quality  
• Manufacturing sorghum noodles with good physical attributes is possible by controlling the flour quality  
• Sorghum cereal had higher PC, AA, and sensory acceptance, but less vitamin E than wheat cereal  
• Rich source of dietary fiber and PC and AA | Liu et al., 2012  
Mkandawire et al., 2015  
Lopes et al., 2018  
Cisse et al., 2018  
Queiroz et al., 2018  
Garzón et al., 2019 |
| Bread                      | Sorghum flour                       | Tannin (R) and nontannin (W) sorghum grain flour                          | • Nontannin sorghum cereal had nutritional and sensory properties comparable to oat cereals  
• Tannin sorghum cereal reduced in vitro protein digestibility  
• Sorghum cereal had higher PC, AA, and sensory acceptance, but less vitamin E than wheat cereal  
• Rich source of dietary fiber and PC and AA | Wolter et al., 2014  
Mkandawire et al., 2015  
Anunciacao et al., 2017  
Anunciacao et al., 2018  
Lopes et al., 2018  
Cisse et al., 2018  
Queiroz et al., 2018  
Garzón et al., 2019 |
| RTE breakfast cereals      | RTE breakfast cereals + unfermented probiotic milk | Tannin sorghum (rich in 3-DA) whole grain | • Reduced oxidative stress and inflammation in people with chronic kidney diseases  
• Traditional African food  
• Slower gastric emptying than other foods (rice, potato, and pasta) | | |
| RTE breakfast cereals + unfermented probiotic milk | RTE breakfast cereals + unfermented probiotic milk | Tannin sorghum (rich in 3-DA) whole grain | • Reduced oxidative stress and inflammation in people with chronic kidney diseases  
• Traditional African food  
• Slower gastric emptying than other foods (rice, potato, and pasta) | | |
| Functional beverages       | Porridge                            | Decorticated grain                                                        | • Traditional African food  
• Slower gastric emptying than other foods (rice, potato, and pasta) | | |
| Grain tea                  | Powder drink                        | Extruded tannin sorghum (rich in 3-DA) whole grain                       | • The PC and AA in this white sorghum grain tea was low  
• Rich source of PC  
• Could improve glycemic response  
• Sorghum tannin had no negative effects on the sensory quality  
• Low in fat and rich source of fibers and proteins  
• High sensory acceptance and purchase intention  
• High bioactive compounds but low alcohol  
• γ-Aminobutyric acid (potential antihypertensive effect), PC, and AA were increased during the brewing process  
• Exhibited antihypertensive and α-glucosidase inhibitory activity | Anunciacao et al., 2018  
Queiroz et al., 2018  
Garzón et al., 2019 |
<table>
<thead>
<tr>
<th>Applications</th>
<th>Food types</th>
<th>Sorghum components/ingredients</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incorporation® Improve food quality and health function</td>
<td>Pasta</td>
<td>Whole grain flour (W, R)</td>
<td>• 20% to 40% incorporation in pasta</td>
<td>Khan et al., 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole grain flour (W, R)</td>
<td>• Increased PC and AA in pasta</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole grain flour (W, R)</td>
<td>• Increased resistant starch in pasta</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole grain flour (R)</td>
<td>• 30% incorporation in pasta</td>
<td>Khan et al., 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole grain flour (R)</td>
<td>• Reduced starch digestibility while maintaining adequate cooking and sensory quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Muffin</td>
<td>Whole grain flour</td>
<td>• Increased PC and AA and reduced oxidative stress in human</td>
<td>Khan et al., 2015</td>
</tr>
<tr>
<td></td>
<td>Chinese steamed bread</td>
<td>Whole grain flour (W, R)</td>
<td>• Could improve glycemic response</td>
<td>Poquette et al., 2014</td>
</tr>
<tr>
<td>As an alternative starch ingredient</td>
<td>Pet food</td>
<td>Tannin sorghum whole grain, flour and milling (R)</td>
<td>• Starch ingredient (wheat, rice, and maize) replacer in extruded dry dog food</td>
<td>Di Donfrancesco &amp; Koppel, 2017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tannin sorghum whole grain, flour and milling (R)</td>
<td>• Starch ingredient (wheat, rice, and maize) replacer in extruded dry dog food</td>
<td>Di Donfrancesco et al., 2018</td>
</tr>
<tr>
<td>Improve animal health and production</td>
<td>Animal feed</td>
<td>Distiller’s grains (with solubles)</td>
<td>• 300 to 350 g/kg incorporation in growing and finishing pig feed</td>
<td>García et al., 2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distiller’s grains (with solubles)</td>
<td>• Reduced the feed costs</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>• No negative effects on growth performance and carcass yield</td>
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<td></td>
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<td>• Increased back fat levels in pigs</td>
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<td></td>
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<td></td>
<td>• 75 g/kg incorporation in rabbit feed</td>
<td>Yang et al., 2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• No negative effects on growth performance and carcass traits, immunity</td>
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<td>• Adverse effects when the addition was higher than 75 g/kg</td>
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(continued)
### Table 4–Continued.

<table>
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<tr>
<th>Applications</th>
<th>Food types</th>
<th>Sorghum components/ingredients</th>
<th>Comments</th>
<th>References</th>
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</thead>
</table>
| Improve food quality and preservation                   | Meat products       | High tannin sorghum bran (Br, Bl) | • 0.25% to 0.75% incorporation in bratwurst, precooked pork, and turkey patties  
• No negative effects on sensory flavor attributes  
• As effective as synthetic antioxidants  
BHA/BHT in meat preservation                        | Luckemeyer et al., 2015 |
|                                                         |                     |                                | • 0.5% incorporation in pork pizza topping and dark chicken meat         | Cabral et al., 2019                             |
|                                                         |                     |                                | • Reduced lipid oxidation and rancid flavor                             |                                                 |
|                                                         |                     |                                | • Resulted in darker color and sorghum flavor                           |                                                 |

#### Phenolics<sup>c</sup>

**As multifunctional food colorants**

| Food in general | 3-Deoxyanthocyanidins | Natural water-soluble pigments (orange/red to blue/violet)  
• Heat, pH, and food bleaching agents resistant  
• Plant phytoalexins and have antimicrobial activities  
• Potent antioxidants  
• Has many potential health benefits  
• Exhibit photochromic properties  
• Very potent antioxidants | Aida et al., 1996; Akogou et al., 2018; Awika et al., 2004; Mihara et al., 2018; Owang & Awika, 2010; Stonecipher et al., 1993; Yang et al., 2014 |

**As multifunctional food antioxidants**

| Food in general | Condensed tannins | Has many potential health benefits  
• Form complexes with proteins and starch that resistant to digestion  
• Natural gluten strengtheners and more effective than tannic acids  
• Can expand in novel food and drug applications  
• May have negative effect on the sensory | Amoako & Awika, 2019; Awika, Rooney, Wu, Prior, & Casneros-Zevallos, 2003a; Dykes & Rooney, 2007; Girard et al., 2016; Girard et al., 2019; Hagerman et al., 1998; Selma et al., 2009 |

<sup>a</sup> Application of sorghum grain to make healthy and functional food: all gluten-free food,  
<sup>b</sup> Incorporating sorghum in food.  
<sup>c</sup> Application of sorghum phenolic compounds in food.  
3-DA, 3-deoxyanthocyanidins; RT, ready-to-eat; PC, phenolic contents; AA, in vitro antioxidant activity; W, white sorghum; R, red sorghum; Br, brown sorghum; Bl, black sorghum; SDS, slowly digestible starch; RS, resistant starch.
Sorghum grain...
(low in phenolic compounds) significantly improved the health status in healthy people by increasing the plasma phenolic contents and antioxidant activity (Khan, Yousif, Johnson, & Gamelath, 2015). Also, sorghum can be very useful in muffin preparation, and muffins containing sorghum have been shown to have high resistant starch and slowly digestible starch contents (Poquette et al., 2014). Sorghum can also be used to improve the health function of Chinese steamed bread. Wu et al. (2018) have shown that incorporation of white or red sorghum whole grain flour into bread, at a 30% substitution level for wheat flour, significantly enhanced the phenolic contents and antioxidant activity.

Because some sorghums, particularly tannin sorghums, may have antinutritional effects and reduce the feed efficiency in animal production, sorghum is poorly utilized and represents one of least used grains in animal foods (Di Donfrancesco & Koppel, 2017). However, sorghum may be an alternative starch ingredient in pet food formulations. Di Donfrancesco and Koppel reported that extruded dog food manufactured with red tannin sorghum (whole grain, flour, or milling) had a similar aroma profile to the commercial dog food made with wheat, rice, and maize. The aroma intensity may not be as strong as the commercial one and may require additional ingredients to make it more palatable. Nevertheless, the dog food made with sorghum fractions has shown similar nutritional composition and pet and pet owner acceptance as commercial dog food (Di Donfrancesco, Koppel, & Aldrich, 2018).

Sorghum is also a potential animal feed additive to improve animal health and production. It has been shown that sorghum distillers’ grain, an industrial by-product from ethanol production, can be used as an additive in pig and rabbit feeds (García, Hernández, Bonet, Coma, & Andrés, 2012; Yang et al., 2019). Sorghum distillers’ grain is a cheap material and is rich in immune activators, which arises from fermentation, and thus promote the immune health in animals (Pomerenke, Souza, & Shurtleff, 2010). Studies have demonstrated that inclusion of 300 to 350 g/kg sorghum distillers’ grain in growing and finishing pig feed increased the pig back-fat levels and had no negative effects on the growth performance and carcass yield (García et al., 2012). Similarly, the inclusion of 75 g/kg sorghum distillers’ grain in rabbit feed showed no negative effects on the growth performance and carcass traits (Yang et al., 2019). It should be noted that excess addition may significantly enhance the animals’ immune system and health, but may also compromise the growth performance and carcass traits; good animal feeding practice can be achieved if sorghum is added in moderation (Yang et al., 2019).

Apart from the whole grain, some sorghum components such as sorghum bran also have a huge potential in food applications. Sorghum bran is a high-value functional ingredient (Awika & Rooney, 2004). The bran can be easily obtained by grain decortication and then used as a natural colorant and antioxidant preservative in food products to improve food quality and preservation, and its functionality in foods can be achieved at a low level of use. For instance, the addition of 0.25% to 0.75% high-tannin sorghum bran to meat products such as precooked pork and turkey patties was reported to prevent the lipid oxidation during storage, and was as effective as the synthetic antioxidants BHA/BHT, without compromising the meat sensory flavor attributes (Luckemeyer et al., 2015). Similarly, the addition of 0.5% high-tannin sorghum bran to pork pizza topping and dark chicken meat was reported to reduce lipid oxidation and rancid flavor (Cabra et al., 2019). Although the addition of sorghum bran to meat products may also lead to a darker color and sorghum flavor (Cabra et al., 2019), it does not necessarily indicate a poor meat quality or low consumer acceptance. The use of natural ingredients to improve the food quality, safety, and health function while maintaining the sensory quality could be an interesting topic for future research.

**The potential application of sorghum phenolic compounds**

The intended functional and beneficial effects of sorghum are contributed mainly by its bioactive compounds. Extraction and isolation of these compounds from sorghum is another option to fully exploit their application potential. Among the sorghum bioactive compounds, 3-deoxyanthocyanidins and condensed tannins could be used as promising multifunctional food additives.

3-Deoxyanthocyanidins could be used as multifunctional food colorants, as they are unique in many ways. They are water-soluble pigments with excellent color stability. Depending on the structure difference and pH conditions, they are responsible for orange/red (acidic pH) to blue/violet colors (alkaline pH) (Grotewold, 2006; Tanaka, Brugliera, & Chandler, 2009). 3-Deoxyanthocyanidins have a number of advantages compared to their anthocyanin analogs. First, 3-deoxyanthocyanidins are more resistant to pH changes and have shown enhanced color intensity at alkaline pH where anthocyanins could not (and normally degrade; Akogou, Kayodé, den Besten, Linnemann, & Fogliano, 2018; Awika et al., 2004). Second, they are more stable and heat resistant and have shown good stability even after severe heat treatment at 121 °C (Akogou et al., 2018; Yang, Dykes, & Awika, 2014). Third, they are also more resistant to food bleaching agents such as ascorbic acid and sulfites (Ojwang & Awika, 2008; Ojwang & Awika, 2010).

3-Deoxyanthocyanidins are also plant phytoalexins with antimicrobial activity. Studies have demonstrated that 3-deoxyanthocyanidins are effective against a range of fungi and bacteria in vitro (Aida, Tamogami, Kodama, & Tsukiboshi, 1996; Stonecipher, Hurley, & Netzly, 1993), although a recent study showed no significant antimicrobial effect on an African food Waga-gshi (Akogou, Besten, Kayode, Fogliano, & Linnemann, 2018). Nevertheless, 3-deoxyanthocyanidins could play a role in food preservation, reducing and possibly replacing the synthetic antimicrobial additives in foods. Additionally, 3-deoxyanthocyanidins are photochromic compounds capable of changes in color in response to light radiation (Mihara, Tasaki, Kohno, & Shibata, 2018; Yagishita, Mihara, Kohno, & Shibata, 2016). This photochromic property can be potentially used to develop photochromic foods, such as color changeable candies, providing additional value and attractiveness to foods. Besides, as mentioned above, 3-deoxyanthocyanidins are potent antioxidants and have anti-inflammatory and anticancer activities (Awika et al., 2009; Makanjuola et al., 2018; Shih et al., 2007; Yang et al., 2009), so they could be added in food as therapeutic agents to prevent some chronic diseases. 3-Deoxyanthocyanidins are promising natural and multifunctional colorants in the food system.

Sorghum condensed tannins are very potent antioxidants. As mentioned above, high tannin sorghum has shown strong antioxidant activity in meat preservation (Luckemeyer et al., 2015). It could be extracted and used as a powerful natural food antioxidant in broader food applications. On the other hand, tannins are notorious for their bitterness and astringency and may have negative impacts on the sensory attributes, and have long been considered as “toxic” compounds (Dykes et al., 2005; Kobue-Lekalale, Taylor, & De Kock, 2007), so their application in foods has been hindered. However, in some foods, sorghum tannins have not

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**Sorghum grain...**

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been found to have any negative impact on the sensory attributes (Kobuc–Lekalake et al., 2007; Queiroz et al., 2018). It has been suggested that sorghum tannins will bind with proteins and other macromolecules and become unavailable to taste receptors (Girard & Awika, 2018). Therefore, the negative sensory impact of sorghum tannins could be minimized by appropriate food formulation and/or food processing methods. The “toxic” effect is now known as the antinutritional effect because tannins can interact with macromolecules (that is, mainly protein and starch) and some minerals (such as iron and zinc) to form bulk complexes that are resistant to digestion (Makkar, 2003). Also, the free form tannins can bind to digestive enzymes, and thus inhibit enzymatic activities, which further reduces the nutritious value of foods (Awika & Rooney, 2004; Mitaru, Reichert, & Blair, 1984). Despite these facts, tannin foods have been consumed by people for thousands of years, and sorghum condensed tannin is an excellent ingredient for people with obesity, diabetes, and cardiovascular problems, as discussed above. Most of the condensed tannins remain undamaged before reaching the lower gastrointestinal tract where they are partially broken down by intestinal microflora into a variety of absorbable phenolic acids, promoting gut and human health (Selma, Espín, & Tomás-Barberán, 2009; Serrano, Puupponen-Pimiä, Dauer, Aura, & Saura-Calixto, 2009). Recently, Anoako and Awika (2019) have uncovered the mechanisms about the complexation of condensed tannin and starch. The condensed tannins can form type II semicrystalline intrahelical V-complexes with amylose, which are highly resistant to α-amylase and amyloglucosidase hydrolysis. This finding provides opportunities to modify starch as bioactive starch ingredients and development of functional foods or nutraceuticals.

Attempts have already been initiated to use sorghum tannin to develop functional foods/nutraceuticals. Recently, Links et al. (2015) developed a nutraceutical by encapsulating sorghum condensed tannins into kafirin microparticles. This nutraceutical can withstand gastric digestion and has shown good anti-hyperglycemic effect both in vitro and in vivo (Links et al., 2015; Links, Taylor, Kruger, Naidoo, & Taylor, 2016). In addition, condensed tannins are strong gluten strengtheners, especially those with large molecular weight and high DP, which are capable to form extensive cross-linking with gluten proteins (Girard, Tefera, & Awika, 2019). Studies have shown that sorghum condensed tannins can significantly increase dough and batter viscosity and stability, thereby improving food structural stability and quality (Girard et al., 2019; Girard, Castell-Perez, Bean, Adrianos, & Awika, 2016). Sorghum condensed tannin could be used as a natural ingredient to improve gluten quality and expand its functionality, suggesting its potential to be developed as a multifunctional ingredient in food and biomedical applications.

As discussed above, sorghum has been traditionally used to make various steamed, boiled products, baked foods, and deep-fried and fermented food/beverage products. Today, advanced food science and technology is exploiting its novel applications in food systems. The whole grains could be developed as functional snacks, foods, and beverages. The whole grains or fractions (for example, bran) are also valuable ingredients that have great potential to be incorporated into other foods, for both humans and animals, to improve the food quality, safety, and health functions. The phenolic compounds can be extracted as natural multifunctional food additives replacing synthetic ones. Particularly, the unique properties of 3-deoxyanthocyanidins in sorghum grain offer huge potential for broader applications (Xiong et al., 2019).

Conclusion and Future Perspectives

Sorghum is an important global cereal crop with very high nutritional and health value. In particular, it has high concentrations and a wide variety of phenolic compounds that may not often be found in other cereal grains. The phenolic compounds in sorghum grain are concentrated in the bran layer, and the composition, concentration, and the extractability of the phenolic compounds differ significantly between sorghum varieties and genotypes. Extensive research has been conducted to investigate the phenolic profile in sorghum, most of them are focusing on the total contents (total phenolic, flavonoids, or condensed tannin contents) using colorimetric methods, rather than the individual phenolics. As the phenolic profile in sorghum is strongly associated with its bioactive properties, the knowledge of the phenolic structure, composition, and its location (that is, bran and kernel) and form of presence (that is, free and bound) in sorghum grain is crucial for extraction method and material selection and processing design, and tailored for specific needs. Further work is required to better understand the phenolic profile of sorghum.

The modern genetic engineering and breeding tools provide exciting opportunities to develop sorghum with desirable nutritional and phenolic profile while maintaining good agronomic performance and yield, and this could be a fruitful area for further research. It has been shown that through mutagenesis-assisted breeding, the biosynthesis of phenolic compounds can be enhanced in sorghum. A sorghum mutagenesis variant, REDforGREEN, which can significantly increase the 3-deoxyanthocyanidins, condensed tannins, and total phenolic contents in sorghum leaf, has been identified (Petti et al., 2014). Advances have also been made in breeding sorghum (germplasms ATx3363 and BTx3363) with high levels of 3-deoxyanthocyanidins in the grain pericarp and with satisfying grain yield (Rooney et al., 2013; Rooney, Rooney, Awika, & Dykes, 2013).

Extensive research has also been conducted to investigate the health effects of sorghum. Evidence has been shown that sorghum possesses potential antioxidant, anti-inflammatory, and anticancer activities, and could improve glycemic response and insulin-related disorders, prevent dyslipidemia and cardiovascular diseases, and influence gut microbiota and promote colonic health. However, most of the evidence is based on in vitro studies, and more in vivo and possibly clinical studies are needed to confirm these health benefits, as well as the interactions between the bioactive compounds and the mechanisms involved.

Despite the health-promoting benefits, the use of sorghum has declined in the regions where sorghum has been traditionally used as the main staple food as people become wealthier and shift to a more Western-based diet. The use of sorghum food requires more advertising and promotion. The development and applications of sorghum in the food system are still in the early stages. Progress has already been made to use sorghum grain to make functional foods, as well as incorporating sorghum grain or components in foods to improve food quality and functionality. Additionally, sorghum 3-deoxyanthocyanidins and condensed tannins are high-value natural ingredients. Due to their diverse functional properties, they could be used as multifunctional food additives to improve food quality, safety, and health function and add value to food products. However, the application of sorghum grain/ingredients in the food system still faces numerous challenges. For example, lack of extraction or isolation methods for individual phenolic compounds (for example, 3-deoxyanthocyanidins or condensed tannins), potential negative sensory impacts associated with sorghum tannin,
and lack of available advanced processing technologies. These problems need to be addressed by food scientists and engineers to have a successful and brand-new era for sorghum food processing to benefit both the food industry and improve human health.

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Author Contributions
Yun Xiong has conceived the manuscript concept and design, and drafting, editing, and proofreading the manuscript. Pangzhen Zhang and Robyn Dorothy Warner have aided in editing and proofreading and provided critical feedback for revision. Zhongxiang Fang has made a substantial contribution in the manuscript concept and design, aided in drafting and revising, and has given final approval of the submission.

Conflict of Interest
The authors declare no conflict of interest.

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