Finger Millet Bioactive Compounds, Bioaccessibility, and Potential Health Effects – a Review

Henry Okwudili UDEH[1], Kwaku Gyebi DUODU[2] and Afam Israel Obiefuna JIDEANI[1]*

[1]Department of Food Science and Technology, School of Agriculture, University of Venda, Thohoyandou, South Africa; [2]Department of Food Science, Faculty of Natural and Agricultural Sciences, University of Pretoria, Hatfield, South Africa

*Corresponding author: Afam.Jideani@univen.ac.za

Abstract

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Finger millet is among minor cereal grains that are underutilised. However, over the years, research interest in the millet has increased owing to its abundance of bioactive compounds. These compounds which include, among others, ferulic acid-rich arabinoxylans or feraxans, ferulic acid, caffeic acid, and quercetin have been associated with certain health promoting properties and have been found bioaccessible in the grain. Following the recent interest in natural curative substances over their synthetic counterparts in the treatment of food dependent diseases, finger millet has shown potential nutraceutical effects. Some important health effects such as antidiabetic, antioxidative, anti-inflammatory and antimicrobial properties have been reported in recent trials with the grain. This review emphasises the dietary fibre – arabinoxylan, and phenolic compounds of finger millet and their properties, and further discusses available evidence on their bioaccessibility and bioactivity. The information presented will further explore the potential of finger millet utilisation, its bioactive compounds, bioaccessibility, and potential health benefits, in view of stimulating further research.

Keywords: *Eleusine coracana*; arabinoxylan; phenolic acids; flavonoids; bioactivity

Finger millet is one of the important millets in the world, serving as staple to millions of economically disadvantaged people in the African and Asian countries. The grain is known under several local names but it is often referred to as *ragi* in India, a name which has been rapidly adopted for the grain. Taxonomically, finger millet belongs to the family *Panicoideae* with five races; *coracana*, *vulgaris*, *elongata*, *plana*, and *compacta* (Seetharam *et al.* 1986; Tatham *et al.* 1996). The race *coracana* is particularly adapted to the arid and semi-arid agro-ecosystem of the eastern highlands of Africa and Ghats of India, with *vulgaris* reported to be grown in Uganda, Ethiopia, and South Africa (Seetharam *et al.* 1986).

Finger millet grains are small-seeded caryopses (about 1.2–1.8 mm in diameter), mostly spherical in shape, having light brown or brick red coloured seed coat with the thin membranous pericarp which is loosely attached covering the entire seed that usually detaches during harvest or simple abrasion (Chethan & Malleshi 2007; Shobana & Malleshi 2007). Although dark brown and black coloured seed varieties are plentiful, they are not so popular. Traditionally, they are either processed by malting or fermentation, of which the resultant flour or extract is widely used in weaning and geriatric foods, beverages, and certain therapeutic products (Subba Rao & Muralikrishna 2001).

In recent years, research interest in finger millet has increased owing to its abundance of bioactive com-

pounds. These bioactive compounds, which include ferulic acid, quercetin, and ferulic-rich arabinoxylans or feraxans among others, have been reported to exhibit important therapeutic effects. Some important health effects such as antioxidative, anti-inflammatory, and antimicrobial properties have been reported in recent trials with the millet (Sripriya *et al.* 1996; Anthony *et al.* 1998; Kumari & Sumathi 2002; Rajasekaran *et al.* 2004; Chethan & Malleshi 2007; Shobana & Malleshi 2007; Banerjee *et al.* 2012; Shahidi & Chandrasekara 2013). Information on finger millet, however, is fast accumulating with available literatures, scarcely emphatic on their bioactive profiles, bioaccessibility, and possible health benefits. Hence, this paper highlights finger millet production, and then emphasis is laid on the dietary fibre fraction and phenolic compounds of the grain. The review further discusses the bioaccessibility and potential health properties of the millet.

Finger millet production

In general, finger millets are underutilised owing to their minimal inclusion in the commercial food system, presumed nutritional irrelevance, lack of research, and applicability in novel product development processes. In addition, their very small sizes and subsistent scale of production are a significant technological setback to their utilisation.

Among millet grains in the world, finger millet ranks fourth after pearl millet (*Pennisetum glaucum*), foxtail millet (*Setaria italica*), and proso millet (*Panicum miliaceum*) (Shahidi & Chandrasekara 2015). Production statistics for millets are very poor and fragmentary, making it difficult to obtain a reliable estimate for individual species (ICRISAT/FAO 1996). However, in 1992–1994 and in recent years, about 46–50% was recorded for pearl millet, 10% for finger millet which account for about 3.76 million metric tonnes in 2004, with foxtail and proso millet accounting for 30% globally (ICRISAT/FAO 1996; FAOSTAT 2004; Shahidi & Chandrasekara 2015). Major finger millet producing countries in the world include India, China, Uganda, and Nepal (FAOSTAT 2004). Aside the agronomic advantages that include their ability to thrive in diverse and adverse environmental conditions, easy to cultivate, and giving higher yield with good storability, research findings have shown that finger millets are rich in bioactive compounds that are found to possess important health properties.

Finger millet bioactive compounds

Bioactive compounds of finger millet grain have been increasingly investigated over the years. Several studies carried out on the grain have reported certain groups of biologically active compounds that are also nutritionally important. These compounds

Table 1. Dietary fibre components and mineral content of finger millet

		Amount (%)	References
Dietary fibre components	total dietary fibre	22.0	Shobana & Malleshi (2007)
	soluble dietary fibre	2.5	Shobana & Malleshi (2007)
	insoluble dietary fibre	19.7	Shobana & Malleshi (2007)
	water soluble (NSP)	0.13	Rao & Muralikrishna (2001)
	hemicellulose A	1.4	Rao & Muralikrishna (2001)
	hemicellulose B	1.9	Rao & Muralikrishna (2001)
Minerals	calcium	317.1–398.0	Shobana & Malleshi (2007); Shahidi & Chandrasekara (2013)
	copper	0.2–0.47	Platel *et al.* (2010); Muthamilarasan *et al.* (2016)
	iron	2.12–3.9	Platel *et al.* (2010); Muthamilarasan *et al.* (2016)
	manganese	3.73–5.98	Muthamilarasan *et al.* (2016)
	zinc	1.44–2.31	Shashi *et al.* (2007)
	magnesium	5.49–137	Muthamilarasan *et al.* (2016)
	phosphorous	211.0–320.0	Shobana & Malleshi (2007); Muthamilarasan *et al.* (2016)
	potassium	294.0–1070.0	Shashi *et al.* (2007)
	sodium	0.6–0.9	Shashi *et al.* (2007)

which are clustered around plant nutrients as dietary fibre, minerals and polyphenols, have been found to exhibit potential nutraceutical effects through their participation in several biological systems.

Dietary fibre components of finger millet

Interest in dietary fibre as a bioactive compound is based on the belief that it contributes positively to health and quality of life, and considering its physiological potencies, it has become a food component of interest. Dietary fibre (DF) is a multi-component mixture of plant origin and forms the main food constituent that influences the rate and extent to which blood glucose increases after ingestion of a carbohydrate or analogous carbohydrate food (AACC 2001; FARDET 2010). Primary plant dietary fibres include non-starch polysaccharides, non-α-glucan oligosaccharide, resistance starches, some polyols, and modified starches (LAFIANDRA *et al.* 2014).

In the earlier report of KAMATH and BELAVADY (1980), it was found that dietary fibre makes up about 18.6% of finger millet grain. However, recent studies have shown that DF constitutes about 22.0% of the millet and it includes the non-starch polysaccharides (water-soluble and water-insoluble polysaccharides, hemicellulose A and B), cellulose, pectin, and lignin (NIRMALA *et al.* 2000; SUBBA RAO & MURALIKRISHNA 2001, 2007; AMADOU *et al.* 2013). The non-starch polysaccharides are largely made up of arabinoxylans, with a small amount of β-D-glucans, and both constitute the main component of the soluble dietary fibre fraction of the grain (RAO & MURALIKRISHNA 2001,

2006). Major sugars identified in the polysaccharides were arabinose, xylose, galactose, and glucose, with mannose and rhamnose being present in minute quantities. Table 1 shows a list of the dietary fibre components and mineral contents of finger millet.

Finger millet arabinoxylan

Arabinoxylan is the principal non-starch polysaccharide in the cell walls of cereal grains. Among major cereals, rye grains are the richest source of arabinoxylans followed by wheat and barley grains (BARTLOMIEJ *et al.* 2011). In finger millet, it occurs both in the water-extractable and water-unextractable forms with a low molecular weight of about 139.9–140 kDa (RAO & MURALIKRISHNA 2006, 2007). Arabinoxylans of finger millet are similar to sorghum, rice, and maize bran arabinoxylans and are more complex or branched in structure compared to wheat and barley arabinoxylans. They are highly branched in nature owing to the side chains of the polymer containing not only high amounts of terminally linked arabinose but also high amounts of uronic and ferulic acids, galactose, and small amounts of xylose (RAO & MURALIKRISHNA 2004; IZYDORCZYK & DEXTER 2008). Relatively few studies have been carried out to elucidate the structural characteristics and associated *in vitro* or *in vivo* activity of finger millet arabinoxylans.

Generally, the structure of cereal arabinoxylans is composed of a linear backbone of β-D-xylopyranosyl residues linked through a (1→4) glycosidic bond, with attached residues of α-L-arabinopyranosyl at carbon position either 3 or 2 or both (BARTLOMIEJ *et al.* 2011;
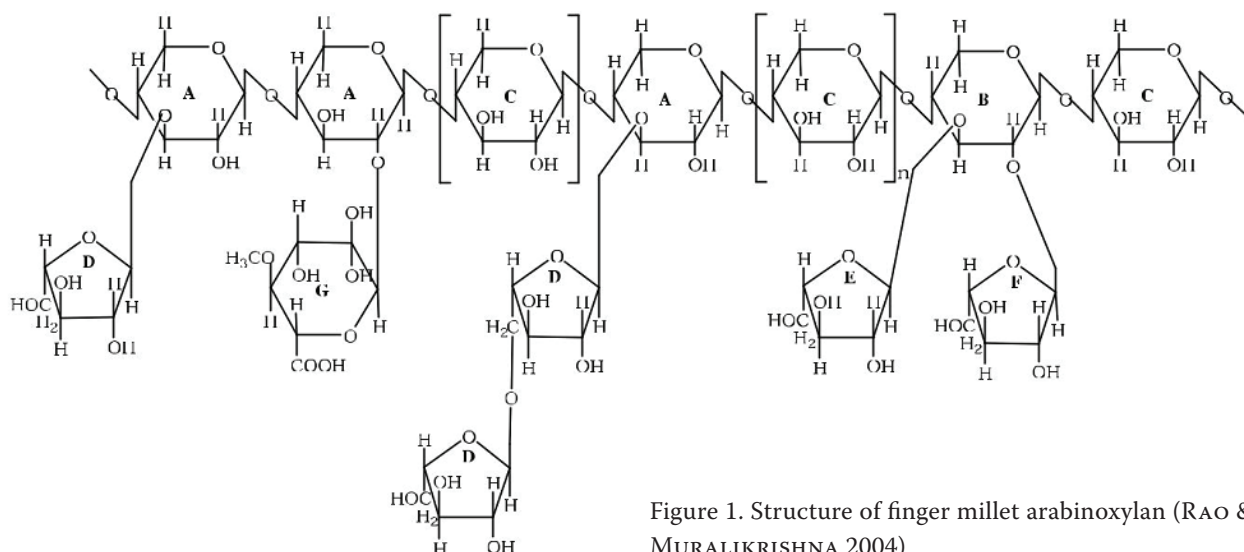

Figure 1. Structure of finger millet arabinoxylan (RAO & MURALIKRISHNA 2004)

Lafiandra *et al.* 2014). The structural analysis of purified arabinoxylans isolated from hemicellulose B of finger millet showed structural similarity to other cereal arabinoxylans. The backbone of the polysaccharide is constituted of 1,4-β-ᴅ-linked xylan units, with the majority of (arabinose and xylose) residue substitutions at carbon position 3 (C-3) (Figure 1) (Subba Rao & Muralikrishna 2004). The report further showed that the polysaccharide is highly branched, composed of high arabinose substitutions at C-3 (di-substituted) or C-2 (mono-substituted) or at both. The present xylose residues were in the mono and un-substituted forms. Similar structural orientation of the residues was also observed for the oligosaccharide obtained from the arabinoxylan. The arabinose substitutions were at C-3 (mono-substituted) and at both C-3 and C-2 in the di-substituted form. Similar xylose substitutions (mono- and un-substituted) were also reported along with a very small amount of di-substitutions (Subba Rao & Muralikrishna 2004). In addition, it was found that the polysaccharide contained up to 10% of uronic acid in the form of glucuronic acid, which is linked to the xylose residues at C-2 (Rao & Muralikrishna 2004, 2006).

Finger millet arabinoxylans have been shown to exhibit high antioxidant activities as a result of their bound phenolic acids. The antioxidative property has been associated with the presence of bound ferulic acids which form a cross-linkage by oxidation to an adjacent arabinoxylan chain. In the report of Rao and Muralikrishna (2006) it was found that the bound ferulic acids were covalently attached to terminal arabinose residues at C-3 of the xylan backbone. These substitutions often result in the formation of ferulate dimers or rarely triferulate residues which are very stable and possess high antioxidant properties (Chandrasekara & Shahidi 2011; Lafiandra *et*

Table 2. Phenolic compounds of finger millet

	Phenolic compounds	Quantity (µg/g)	References
Phenolic acids	**hydroxybenzoic acids**		
	gentisic	4.5	Hithamani & Srinivasan (2014)
	vanillic	20.0	Chethan *et al.* (2008a)
	gallic	3.91–30.0	Chethan *et al.* (2008a); Hithamani & Srinivasan (2014)
	syringic	10.0–60.0	Dykes & Rooney (2007); Hithamani & Srinivasan (2014)
	salicylic	5.12–413.0	Hithamani & Srinivasan (2014)
	protocatechuic	119.8–405.0	Chethan *et al.* (2008a); Hithamani & Srinivasan (2014)
	p-hydroxybenzoic	6.3–370.0	Dykes & Rooney (2007); Chethan *et al.* (2008); Hithamani & Srinivasan (2014)
	hydroxycinnamic acids		
	chlorogenic	–	Shahidi & Chandrasekara (2013)
	caffeic	5.9–10.4	Hithamani & Srinivasan (2014)
	sinapic	11.0–24.8	Hithamani & Srinivasan (2014)
	p-coumaric	1.81–41.1	Chethan *et al.* (2008a); Shahidi & Chandrasekara (2013)
	trans-cinnamic	35–100.0	Chethan *et al.* (2008a); Hithamani & Srinivasan (2014)
	trans-ferulic	41–405.0	Shahidi & Chandrasekara (2013)
Flavonoids	quercetin	3	Chethan *et al.* (2008a)
	catechin gallocatechin, epicatechin, epigallocatechin, taxifolin, vitexin, tricin, luteolin, myricetin, apigenin, kempherol, narigenin, diadzein, procyanidin B1, orientin, isoorientin, isovitexin, saponarin, violanthin, lucenin-1, saponarin, violanthin	–	Rao & Muralikrishna (2002); Chethan *et al.* (2008); Shobana *et al.* (2009); Viswanath *et al.* (2009); Chandrasekara & Shahidi (2011); Banerjee *et al.* (2012); Shahidi & Chandrasekara (2013)

al. 2014). These residues are collectively referred to as feraxans due to their abundance of bound ferulic acids. Their high antioxidant activity is also influenced by the presence of a high amount of uronic acid and as well as their molecular weights (Rao & Muralikrishna 2006, 2007). The structural complexity, bound ferulic acids, and the uronic acid of the arabinoxylan are believed to participate in the health beneficial effects or bioactivities observed in many experimental trials, as will be discussed later in the review.

Phenolic compounds of finger millet

Phenolic compounds are among the most highly diversified groups of phytochemicals found in plant foods and as such constitute an important part of the human diet. They represent several groups of compounds that include hydroxybenzoic acids, hydroxycinnamic acids, flavonoids, stilbenes, and lignans (Naczk & Shahidi 2004; Chandrasekara & Shahidi 2012). Several studies have shown that finger millet exhibits a wide variety of phenolic compounds. The widely studied phenolic compounds in the grain are the phenolic acids and flavonoids. Table 2 shows the amounts of identified phenolic compounds in finger millet. These values might vary on the basis of experimental conditions, assay methods, and grain type employed.

Studies have shown that the brown type of finger millet contains a high proportion of phenolic com-pounds compared to the white type, which are found to concentrate in the seed coat rather than in the flour fraction (Chethan & Malleshi 2007). Sripriya *et al*. (1996) indicated that brown finger millet has a higher (0.1%) polyphenol content than the white counterpart (0.003%) (Chethan & Malleshi 2007). In addition, the earlier work of Ramachandra *et al*. (1977) reported that brown finger millet contains a higher proportion (about 0.12–3.47%) of proanthocya-nins than the white variety (0.04–0.06%). So far, most of the studies have focused on the two major finger millet types, brown and white, with the dark brown and black type rarely reported. It will be important to investigate these varieties to further identify, quantify, and characterise their phenolic compounds.

Like in the case of other cereal grains, phenolic compounds of finger millet also occur in free, con-jugated, and bound forms (Chethan & Malleshi 2007; Chethan *et al*. 2008a; Chandrasekara & Shahidi 2012). Reported amounts of the free, es-terified, etherified, and bound phenolic compounds of finger millet are 1970, 216, 81, and 536 µg/g, respectively, with the total phenolic content ranging from 265 to 373.15 mg/100 g (Shobana & Malleshi 2007; Sreeramulu *et al*. 2009; Shahidi & Chan-drasekara 2013). The content of the soluble (free, esterified, and etherified) and insoluble fractions is the sum of the derivatives of hydroxybenzoic and hydroxycinnamic acids and flavonoids as de-termined in the report of Chandrasekara and Shahidi (2011).

(**A**) Benzoic acid
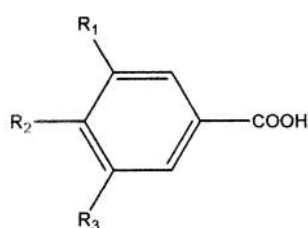
(**B**) Cinnamic acid

Benzoic acid derivatives	Substitutions		
	R_1	R_2	R_3
p-Hydroxybenzoic	H	OH	H
Protocatechiric	H	OH	OH
Vannilic	CH_3O	OH	H
Syringic	CH_3O	OH	CH_3O
Gallic	OH	OH	OH
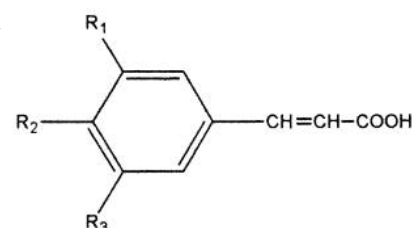
Cinnamic acid derivatives	Substitutions		
	R_1	R_2	R_3
p-Coumaric	H	OH	H
Caffeic	OH	OH	H
Ferulic	CH_3O	OH	H
Sinapic	CH_3O	OH	CH_3O

Figure 2. General structure of phenolic acids: (**A**) benzoic acid and derivatives and (**B**) cinnamic acid and derivatives (Liu 2004)

Phenolic acids

Phenolic acids are derivatives of benzoic and cinnamic acids and are found in all cereals, with sorghum and millets exhibiting the widest variety (Dykes & Rooney 2007; Liu 2007). There exist two classes of phenolic acids: hydroxybenzoic acids which are derived from benzoic acid and hydroxycinnamic acids which are derived from cinnamic acid (Figure 2). The hydroxybenzoic acids form the major free phenolic fraction of finger millet, and constitute about 70–71% of the phenolic acids of the grain. They include gallic acid, protocatechuic, *p*-hydroxybenzoic, vanillic, gentisic, and syringic acids, with protocatechuic acid identified as the main free phenolic acid (45 mg/100 g) (Subba Rao & Muralikrishna 2002; Chandrasekara *et al.* 2012; Hithamani & Srinivasan 2014). However, minute amounts of hydroxycinnamic acids (ferulic, caffeic, and *p*-coumaric acids) are also reported in the free phenolic fraction.

On the other hand, the hydroxycinnamic acids form the majority of the bound phenolic acids of finger millet and they include caffeic, chlorogenic, sinapic, cinnamic (*trans*-cinnamic), coumaric (*p*-coumaric), and ferulic (*trans*-ferulic) acids (Muralikrishna 2001; Subba Rao & Muralikrishna 2002; Chethan & Malleshi 2007; Dykes & Rooney 2007; Chandrasekara *et al.* 2012; Shahidi & Chandrasekara 2013; Hithamani & Srivivasan 2014). They make up about 30% of the phenolic acids of the grain. Ferulic acid is the most abundant bound phenolic acid in millet, followed by caffeic and coumaric acids, with their occurrence in the order of 18.6, 1.64, and 1.20–1.25 mg/100 g flour, respectively (Subba Rao & Muralikrishna 2001, 2002; Dykes & Rooney 2006). The hydroxybenzoic acids, protocatechuic, and syringic acids are also found in trace amounts in the bound fraction.

Flavonoids

Finger millet is a rich source of flavonoid compounds. A variety of the compounds has been identified both from the grain and the leaves of millet, however little has been done to quantify their respective amounts. Finger millet flavonoids are mainly present in the soluble form and have been shown to be higher in an amount of 2100 µg/g compared to other millets (Chandrasekara *et al.* 2012; Shahidi

& Chandrasekara 2013). Esterified forms of flavonoids are also reported in finger millet which are markedly different from flavonoids of other millets such as kodo millet (Shahidi & Chandrasekara 2015). The major flavonoids reported in millet are quercetin, catechin, gallocatechin, epicatechin, and epigallocatechin. In addition, proanthocyanidins or condensed tannins, which are oligomeric or polymeric flaovonoids, are found in a significant amount in the grain; with procyanidin B1 and B2 reported to be the major dimers (Chandrasekara & Shahidi 2012; Shahidi & Chandrasekara 2015).

These phenolic compounds are recognised for their antioxidative, antiproliferative, anti-allergic, and anti-inflammatory properties. However, there are no structural representations of these phenolic compounds peculiar to finger millet; instead, they are presumed to adopt similar structural identity and activity of the compounds in themselves. Therefore, there is a need to characterise the structural forms of these compounds which will be relevant in predicting the bioactivities of the grain with respect to the phenolic compound(s) involved.

Bioaccessibility of finger millet bioactive compounds

Bioaccessibility of plant food nutrients, especially of cereal grains, is a novel scientific area of study, owing to its arbitral description of the importance of food nutrients and health. Although controversies still linger on the working definition, recent studies have rather adopted the definition to be the fraction or amount of food substance from the food matrix that is soluble in the gastrointestinal environment and is available for absorption (Cardoso *et al.* 2015). The release and subsequent activity of bioactive compounds of foods are dependent on their accessibility to an enzymatic attack either from the food or the gastrointestinal tract. The gastrointestinal release of cereal bioactive compounds is very low due to their association with the cell wall matrix components especially dietary fibre, polyphenols, and other antinutritional factors such as phytates and tannins.

Relatively few emerging studies have reported the bioaccessibility potential of finger millet bioactive compounds especially for the minerals and phenolic compounds (Tatala *et al.* 2007; Platel *et al.* 2010; Chandrasekara & Shahidi 2012; Hithamani & Srinivasan 2014). The effect of malting on the

availability and bioaccessibility of iron, zinc, calcium, copper, and manganese in finger millet was evaluated by Platel *et al.* (2010). The report indicated a modest decrease in the mineral contents of millet after malting. However, an increase in bioaccessible iron and calcium was recorded. The malting process is known to reduce antinutritional factors especially phytates, by activating endogenous enzymes such as phytase, which results in their breakdown and subsequent reduction. It is suggested that the decrease in mineral content was a result of the effect of malting on phytates and other antinutritional factors that form complexes with the minerals (Platel *et al.* 2010). In addition, their release may have resulted through the ionisation reaction of the minerals during hydrolysis of the phytate-mineral complex. In another study carried out by Tatala *et al.* (2007), a similar increase in bioaccessible/bioavailable iron (0.75 ± 18 to 1.25 ± 0.5 mg/100 g) was observed after the germination of finger millet grain. The increase in bioaccessible iron could result from the activation of endogenous enzymes such as esterases and phytase which consequently acts on polyphenols or phytate-mineral complexes, in turn resulting in the release of the mineral. The physiological impact was recorded as increases in the haemoglobin and serum ferritin levels in children fed the germinated grain diet for a period of 6 months.

Besides the food structure and antinutritional factors, the processing method is also an important determinant of the bioaccessibility of cereal bioactive compounds. Some of the reported processing methods such as milling, sprouting, roasting, enzymatic digestion, and fermentation, are effective in the release of these compounds by increasing their surface area ratio, inducing the activity of endogenous enzymes and bioconversion of the bioactive compounds to more active compounds. The effect of sprouting, roasting, pressure cooking, open-pan boiling, and microwave heating on the finger millet phenolic profile and their bioaccessibility was evaluated by Hithamani and Srinivasan (2014). Except for roasting, other processing methods brought about a reduction in the total phenolic acids and flavonoid contents. The reduction observed in the sprouted grains was attributed to the loss of phenolic compounds during soaking. In the process of germination, endogenous phenolic enzymes are activated, resulting in their hydrolysis and consequent loss during soaking. On the other hand, sprouting and roasting were found to have a positive impact on the bioaccessibility of

phenolic compounds in the grain, with an increase of 67% after sprouting. The effect of the processing methods on the food matrix and transformation of the compounds into more active forms could account for the observed increase (Hithamani & Srinivasan 2014).

The effect of simulated gastrointestinal pH conditions, gastric and gastrointestinal digestion, and colonic fermentation on the bioaccessibility of phenolic compounds of finger millet was investigated by Chandrasekara and Shahidi (2012). In all the treatments, higher bioaccessible total phenolics were observed for the gastric and gastrointestinal digesta compared to the pH treatment and colonic fermentation. Digestion of proteins and the subsequent release of their bound phenolics present in the grain were suggested to account for the increase. On the other hand, the activity of endogenous enzymes such as proteases and esterases could also play a role in the release of the phenolic compounds from the cell wall matrix during digestion.

Bioactivity of finger millet grain

Over the years, interest in natural curative substances over the synthetic counterpart has fostered investigations into several food materials with potential health benefits. A few studies on finger millet have indicated some therapeutic effect that could have relevance in some food dependent diseases such as diabetes, obesity, and gastrointestinal tract disorders (Gopalan 1981; Geetha & Parvathi 1990; Tovey 1994; Shobana *et al.* 2010). *Diabetes mellitus* is a complex metabolic disorder characterised by high systemic glucose levels resulting from the impaired insulin secretion, with alterations in carbohydrate, protein, and lipid metabolism (Kumari & Sumathi 2002; Devi *et al.* 2014). In the treatment of *diabetes mellitus*, one preventive approach is to decrease the postprandial hyperglycaemia or glucose surge by blocking or reducing the action of carbohydrate hydrolysing enzymes. α-Amylase and α-glucosidase are important catalytic enzymes that convert carbohydrates into glucose for absorption in the human gut, and their modulation can be relevant in some metabolic conditions especially diabetes.

In the several past years, it has been hypothesised that the regular consumption of finger millet is associated with a reduced risk of diabetes and this property has been attributed to the high polyphenol

and dietary fibre content of the grain (Gopalan 1981; Chethan *et al.* 2008b). This proposition is based on the role of bioactive compounds in the metabolism of food materials especially carbohydrates. Phenolic compounds of finger millet have been shown to have a potential modulatory effect on the breakdown of carbohydrates either by reacting with proteins/enzymes or altering properties of biopolymers. Whereas the high dietary fibre is implicated in lower postprandial glucose and insulin responses owing to its participation/formation of unabsorbable complexes with available carbohydrates (Devi *et al.* 2014; Lafiandra *et al.* 2014). These phenomena often affect carbohydrate digestibility and result in the delay of the systemic absorption of glucose which ultimately controls the postprandial blood glucose surge. In the report of Chethan *et al.* (2008a), finger millet seed coat phenolics were found to reversibly inhibit aldose reductase in a non-competitive mode (Chethan & Malleshi 2007). Aldose reductase is the key enzyme implicated in diabetes induced cataractogenesis (Devi *et al.* 2014). It is suggested that the mechanism of the inhibition of millet polyphenols on aldose reductase is preventing the enzymatic conversion of glyceraldehyde to glycerol and glucose to sorbitol. The structure-activity relationship reveals that the hydroxyl group at position 4 and the neighbouring *O*-methyl group of polyphenols were responsible for the inhibition of the enzyme. In another study by Chethan *et al.* (2008b), finger millet phenolic extracts were found to exert a mixed non-competitive mode of inhibition on the malt amylases, whereas the individual phenolic compounds showed an uncompetitive inhibition. Among the phenolic compounds evaluated, *trans*-cinnamic acid was found to exhibit a higher degree of inhibition of 79.2% with syringic acid showing a weaker inhibition of ~56%. The finding of Shobana *et al.* (2009) was also consistent with this observation. In the study, finger millet seed coat phenolics were found to exhibit a non-competitive inhibition against pancreatic amylase and intestinal α-glucosidase in a dose-dependent manner. The mode of inhibition was suggested to be dependent on the concentration of phenolic compounds as well as the number and position of hydroxyl groups (Rohn *et al.* 2002; Chethan *et al.* 2008a). The competition of phenolic compounds with the substrate for enzyme active site or enzyme substrate specificity phenomenon could also account for the observation.

The oxidation of glycated collagen or glycoxidation presents a risk of complications in the diabetic condition. Hedge *et al.* (2002) demonstrated the effect of a methanolic extract of finger millet and kodo millet on glycation and collagen cross-linking. The results showed inhibited glycation for collagen which was incubated with glucose (50 mM) and 3 mg of the finger millet extract. The inhibitory effect of the finger millet extract was attributed to the antioxidative activities of phenolic compounds present in the extract and other phytochemicals extracted from the seed coat. In another study carried out by Hedge *et al.* (2005), the effect of a methanolic extract of finger millet on collagen cross-linking was evaluated. The results showed that the extract strongly inhibited the glycation reaction compared to the synthetic antioxidants (aminoguanidine, butylated hydroxyanisole). The inhibitory effect was attributed to the phenolic compounds, especially ferulic acid, which has been shown to offer renal protective effects through improved glycaemic control and renal structural changes involved in the inhibition of oxidative stress (Hedge *et al.* 2005; Choi *et al.* 2011). The study of Kumari and Sumathi (2002) showed that the consumption of finger millet-based diets significantly lowered the blood plasma glucose levels in individuals with non-insulin dependent *diabetes mellitus.* Consistently with this report, an earlier work of Geetha and Parvathi (1990) indicated that the supplementation of diets with ragi showed a higher reduction in fasting and postprandial glucose levels than the supplementation with other millet. Evidence on the hyperglycaemic, hypocholesterolaemic, nephroprotective, and anticataractogenic properties of finger millet was demonstrated by Shobana *et al.* (2010). In the study, reduced fasting hyperglycaemia and partial reversal of abnormalities in the serum albumin, urea, and creatinine status were observed in streptozotocin induced diabetic rats. Hypercholesterolaemia, hypertriacylglycerolaemia, nephropathy, and neuropathy associated with diabetes were significantly reversed in a diabetic group fed the diet containing the finger millet seed coat matter (Shobana *et al.* 2010; Devi *et al.* 2014). In addition, finger millet-based diets were found to enhance the antioxidant status and better control the blood glucose levels in rats (Rajasekaran *et al.* 2004). These effects result from the high dietary fibre content of the grain and presence of antinutritional factors known to reduce starch digestibility and glucose diffusion. On the same vein, the phenolic compounds present in the grain may also play a role in the observed effect, as they have been shown to be potential inhibitors of carbohydrate degrading enzymes.

In the later stage of diabetes, dermal injuries are known to worsen, resulting in deep wounds and amputation risk if not properly treated. In a study carried out by Rajasekaran *et al*. (2004), the effect of finger millet feeding on dermal wound healing of induced diabetic rats was evaluated. In the experiment, feeding of diabetic rats with finger millet for a period of 4 weeks resulted in an improved wound healing process. The effect was suggested to be a result of the synergistic activities of different phenolic antioxidants and minerals present in the grain. Consistently with the findings, Hegde *et al*. (2005) also observed a similar effect on the dermal wound healing process in rats upon topical application of an aqueous paste of finger millet flour. The observation was attributed to the high calcium and amino acid (cysteine and methionine) content of the grain, which were suggested to participate in the wound healing process. On the other hand, the effect could also result from the antioxidative and anti-inflammatory properties of the grain phenolic compounds. In addition, the antimicrobial activity of a finger millet polyphenol extract as well as the individual phenolic compounds were determined by Banerjee *et al*. (2012). The millet extract was found to exhibit proliferative inhibitory activities against *Escherichia coli, Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes, Streptococcus pyogenes, Proteus mirabilis, Pseudomonas aeruginosa, Serratia marsescens, Klebsiella pneumonia*, and *Yersinia enterocolitica.* It was suggested that the high phenolic content of millet may have caused the inhibition of microbial enzymes and oxidation of the microbial membranes thus resulting in the proliferation of bacterial cells. In the study, the phenolic compound quercetin was found to exert the highest antiproliferative effect among the phenolic compounds evaluated. This compound is widely known for its pharmaceutical properties including antioxidant, antiapoptotic, and antiproliferative effects.

CONCLUSION

It is evident from the available literature that finger millet contains a significant amount of bioactive compounds that are both bioaccessible and bioactive. However, in coherence with other authors' recommendation, these findings require further validation in human subjects as well as their underlying mechanism of action to well establish the health associated claims. In the future, research on possible diverse application of finger millet should be encouraged to foster the utilisation of the grain, especially in resource-poor segments of the tropics. Research is needed to further identify and quantify the bioactive compounds, particularly flavonoids, as well as their chemical structure and structure-activity properties, which will be important in describing the bioactivities of the grain. Furthermore, an optimisation of processing methods on the bioaccessibility of finger millet bioactive compounds will be desirable, as it will assist in predicting the optimal condition suitable for ensuring a significant amount of bioaccessible bioactive compounds in the grain.

References

Amadou I., Gounga M.E., Le G.W. (2013): Millets: Nutritional composition, some health benefits and processing – a review. Food Science and Nutrition, 25: 501–508.

American Association of Cereal Chemist (2001): The definition of dietary fibre. Cereal Foods World, 46: 112–126.

Anthony U., Mosses L.G., Chandra T.S. (1998): Inhibition of *Salmonella typhimurium* and *Escherichia coli* by fermented flour of finger millet (*Eleusine coracana*). World Journal of Microbiology and Biotechnology, 14: 883–886.

Bartlomiej S., Justyna R., Ewa N. (2011): Bioactive compounds in cereal grains – occurrence, structure, technological significance and nutritional benefits – a review. Food Science and Technology International, 18: 559–568.

Banerjee S., Sanjay K.R., Chethan, S., Malleshi N.G. (2012): Finger millet (*Eleusine coracana*) polyphenols: Investigation of their antioxidant capacity and antimicrobial activity. African Journal of Food Science, 6: 362–374.

Cardoso C., Afonso C., Lourenco H., Costa S., Nunes M.L. (2015): Bioaccessibility assessment methodologies and their consequences for the risk–benefit evaluation of food. Trends in Food Science and Technology, 41: 5–23.

Chandrasekara A., Shahidi F. (2011): Antiproliferative potential and DNA scission inhibitory activity of phenolics from whole millet grains. Journal of Functional Foods, 3: 159–170.

Chandrasekara A., Shahidi F. (2012): Bioaccessibility and antioxidant potential of millet grain phenolics as affected by simulated in vitro digestion and microbial fermentation. Journal of Functional Foods, 4: 226–237.

Chandrasekara A., Naczk M., Shahidi F. (2012): Effect of processing on the antioxidant activity of millet grains. Food Chemistry, 133: 1–9.

Chethan S., Malleshi N.G. (2007): Finger millet polyphenols: Characterization and their nutraceutical potential. American Journal of Food Technology, 2: 582–592.

Chethan S., Dharmesh S.M., Malleshi N.G. (2008a): Inhibition of aldose reductase from cataracted eye lenses by finger millet (*Eleusine coracana*) polyphenols. Bioorganic and Medicinal Chemistry, 16: 10085–10090.

Chethan S., Dharmesh S.M., Malleshi N.G. (2008b): Inhibition of aldose reductase from cataracted eye lenses by finger millet (*Eleusine coracana*) polyphenols. Bioorganic and Medicinal Chemistry, 16: 10085–10090.

Choi R., Kim B.H., Naowaboot J., Lee M.Y., Hyun M.R., Cho E.J., Lee E.S., Lee E.Y., Yang Y.C., Chung C.H. (2011): Effects of ferulic acid on diabetic nepropathy in a rat model of type 2 diabetes. Experimental and Molecular Medicine, 43: 676–683.

Devi P.B., Vijayabharathi R., Sathyabama S., Malleshi N.G., Priyadarisini V.B. (2014): Health benefits of finger millet (*Eleusine coracana* L.) polyphenols and dietary fibre: a review. Journal of Food Science and Technology, 51: 1021–1040.

Dykes L., Rooney L.W. (2006): Sorghum and millet phenols and antioxidants. Journal of Cereal Science, 44: 236–251.

Dykes L., Rooney L.W. (2007): Phenolic compounds in cereal grains and their health benefits. Cereal Foods World, 52: 105–111.

Fardet A. (2010): New hypotheses for the health-protective mechanisms of whole-grain cereals: what is beyond fibre? Nutrition Research Review, 23: 65–134.

FAOSTAT (2004): Food and Agriculture Organization Statistical Database. Available at www.faostat.fat.org (accessed Aug 27, 2015).

Geetha C., Parvathi E.P. (1990): Hypoglycaemic effect of millet incorporated breakfast on selected non-insulin dependent diabetic patients. The Indian Journal of Nutrition and Dietetics, 27: 316–320.

Gopalan C. (1981): Carbohydrates in diabetic diet. Bulletin of Nutrition Foundation, India, 3.

Hegde P.S., Anitha B., Chandra T.S. (2005): *In vivo* effect of whole grain flour of finger millet (*Eleusine coracana*) and kodo millet (*Paspalum scrobiculatum*) on rat dermal wound healing. Indian Journal of Experimental Biology, 43: 254–258.

Hedge P.S., Chandrakasan G., Chandra T.S. (2002): Inhibition of collagen glycation and cross linking *in vitro* by methanolic extracts of Finger millet (*Eleusine coracana*) and Kodo millet (*Paspalum scrobiculatum*). Journal of Nutritional Biochemistry, 13: 517–521.

Hithamani G., Srinivasan K. (2014): Effect of domestic processing on the polyphenol content and bioaccessibility in finger millet (*Eleusine coracana*) and pearl millet (*Pennisetum glaucum*). Food Chemistry, 164: 55–62.

ICRISAT/FAO (1996): The World Sorghum and Millet Economies: Facts, Trends and Outlook. Monograph. International Crops Research Institute for the Semi-Arid Tropics.

Izydorczyk M.S., Dexter J.E. (2008): Barley β-glucans and arabinoxylans: Molecular structure, physicochemical properties and uses in food products – a review. Food Research International, 41: 850–868.

Kamath M.V., Belavady B. (1980): Unavailable carbohydrates of commonly consumed Indian foods. Journal of the Science of Food and Agriculture, 31: 194–202.

Kumari L., Sumathi S. (2002): Effect of consumption of finger millet on hyperglycemia in non-insulin dependent diabetes mellitus (NIDDM) subjects. Plant Foods for Human Nutrition, 57: 205–213.

Lafiandra D., Riccardi G., Shewry P.R. (2014): Review – Improving cereal grain carbohydrates for diet and health. Journal of Cereal Science, 59: 312–326.

Liu R.H. (2004): Potential synergy of phytochemicals in cancer prevention: Mechanism of action. The Journal of Nutrition, 134: 3479–3485.

Liu R.H. (2007): Whole grain phytochemicals and health. Journal of Cereal Science, 46: 207–219.

Muthamilarasan M., Dhaka A., Yadav R., Prasad M. (2016): Exploration of millet models for developing nutrient rich graminaceous crops. Plant Science, 242: 89–97.

Naczk M., Shahidi F. (2004): Extraction and analysis of phenolics in food. Journal of Chromatography, 1054: 95–111.

Nirmala M., Subba Rao M.V.S.S.T., Muralikrishna G. (2000): Carbohydrates and their degrading enzymes from native and malted finger millet (Ragi, *Eleusine coracana*, Indaf-15). Food Chemistry, 69: 175–180.

Platel K., Eipeson S.W., Srinivasan K. (2010): Bioaccessible mineral content of malted finger millet (*Eleusine coracana*), wheat (*Triticum aestivum*), and barley (*Hordeum vulgare*). Journal of Agricultural and Food Chemistry, 58: 8100–8103.

Rajasekaran N.S., Nithya M., Rose C., Chandra T.S. (2004): The effect of finger millet feeding on the early responses during the process of wound healing in diabetic rats. Biochimica Biophysica Acta, 1689: 190–201.

Ramachandra G., Virupaksha T.K., Shadaksharaswamy M. (1977): Relationship between tannin levels and in vitro protein digestibility in finger millet (*Eleusine coracana* Gaertn.). Journal of Agricultural and Food Chemistry, 25: 1101–1104.

Rao R.S.P., Muralikrishna G. (2006): Water soluble feruloyl arabinoxylans from rice and ragi: changes upon malting and their consequence on antioxidant activity. Phytochemistry, 67: 91–99.

Rao R.S.P., Muralikrishna G. (2007): Structural characteristics of water-soluble feruloyl arabinoxylans from rice (*Oryza sativa*) and ragi (finger millet, *Eleusine coracana*): variations upon malting. Food Chemistry, 104: 1160–1170.

Rohn S., Rawel H.M., Kroll J. (2002): Inhibitory effects of plant phenols on the activity of selected enzymes. Journal of Agricultural and Food Chemistry, 50: 3566–3571.

Seetharam A., Riley K.W., Harinarayana G. (1986): Small millets in global agriculture. In: Proceedings of the First International Small Millets Workshop, Oct 29–Nov 2, 1986, Bangalore, India: 21–23.

Shahidi F., Chandrasekara A. (2013): Millet grain phenolics and their role in disease risk reduction and health promotion: a review. Journal of Functional Foods, 5: 570–581.

Shahidi F., Chandrasekara A. (2015): Processing of millet grains and effects on non-nutrient antioxidant compounds. In: Preedy V. (ed.): Processing and Impact on Active Components in Food. San Diego, Elsevier Science Publishing Co. Inc.: 345–352.

Shashi B.K., Sharan S., Hittalamani S., Shankar A.G., Nagarathna T.K. (2007): Micronutrient composition, antinutritional factors and bioaccessibility of iron in different finger millet (*Eleusine coracana*) genotypes. Karnataka Journal of Agricultural Science, 20: 583–585.

Shobana S., Harsha M.R., Platel K., Srinivasan K., Malleshi N.G. (2010): Amelioration of hyperglycaemia and its associated complications by finger millet (*Eleusine coracana* L.) seed coat matter in streptozotocin-induced diabetic rats. British Journal of Nutrition, 104: 1787–1795.

Shobana S., Sreerama Y.N., Malleshi N.G. (2009): Composition and enzyme inhibitory properties of finger millet (*Eleusine coracana* L.) seed coat phenolics: Mode of inhibition of alpha-glucosidase and pancreatic amylase. Food Chemistry, 115: 1268–1273.

Shobana S., Malleshi N.G. (2007): Preparation and functional properties of decorticated finger millet (*Eleusine coracana*). Journal of Food Engineering, 79: 529–538.

Sreeramulu D., Reddy C.V.K., Raghunath M. (2009): Antioxidant activity of commonly consumed cereals, millets, pulses and legumes in India. Indian Journal of Biochemistry and Biophysics, 46: 112–115.

Sripriya G., Chandrasekharan K., Murty V.S., Chandra T.S. (1996): ESR spectroscopic studies on free radical quenching action of finger millet (*Eleusine coracana*). Food Chemistry, 57: 537–540.

Subba Rao M.V.S.S.T., Muralikrishna G. (2001): Non-starch polysaccharides and bound phenolic acids from native and malted finger millet (Ragi*, Eleusine coracana*, Indaf - 15). Food Chemistry, 72: 187–192.

Subba Rao M.V.S.S.T., Muralikrishna G. (2002). Evaluation of the antioxidant properties of free and bound phenolic acids from native and malted finger millet (Ragi, *Elucine coracana* Indaf-15). Journal of Agricultural and Food Chemistry, 50: 889–892.

Subba Rao M.V.S.S.T.S., Muralikrishna G. (2004): Structural analysis of arabinoxylans isolated from native and malted finger millet (*Eleusine coracana*, ragi). Carbohydrate Research, 339: 2457–2463.

Tatala S., Ndossi G., Ash D., Mamiro P. (2007): Effect of germination of finger millet on nutritional value of foods and effect of food supplement on nutrition and anaemia status in Tanzanian children. Tanzanian Health Research Bulletin, 9: 77–86.

Tatham A.S., Fido R.J., Moore C.M., Kasarda D.D., Kuzmicky D.D., Keen J.N., Shewry P.R. (1996): Characterization of the major prolamins of tef (*Eragrostis tef*) and finger Millet (*Eleusine coracana*). Journal of Cereal Science, 24: 65–71.

Tovey F.I. (1994): Diet and duodenal ulcer. Journal of Gastroenterology and Hepatology, 9: 177–185.

Viswanath V., Urooj A., Malleshi N.G. (2009): Evaluation of antioxidant and antimicrobial properties of finger millet (*Eleusine coracana*). Food Chemistry, 114: 340–346.