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Review

Potential use of pearl millet (*Pennisetum glaucum* (L.) R. Br.) in Brazil: Food security, processing, health benefits and nutritional products

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ABSTRACT

Climate change can cause an increase in arid soils, warmer weather, and reduce water availability, which in turn can directly affect food security. This increases food prices and reduces the availability of food. Therefore, knowledge concerning the nutritional and technological potential of non-traditional crops and their resistance to heat and drought is very interesting. Pearl millet is known to produce small nutritious cereal grains, which can endure both heat and dry conditions, and is one of the basic cereals of several African and Asian countries. Although this species has been cultivated in Brazil for at least 50 years it is only used as a cover crop and animal feed, but not for human consumption. Nonetheless, pearl millet grains have a high potential as food for humans because they are gluten-free, higher in dietary fiber content than rice, similar in lipid content to maize and higher content of essential amino acids (leucine, isoleucine and lysine) than other traditional cereals, such as wheat and rye. In addition, the crop is low cost and less susceptible to contamination by aflatoxins compared to corn, for example. Most grains, including pearl millet, can be milled, decorticated, germinated, fermented, cooked and extruded to obtain products such as flours, biscuits, snacks, pasta and non-dairy probiotic beverages. Pearl millet also has functional properties; it has a low glycemic index and therefore it can be used as an alternative food for weight control and to reduce the risk of chronic diseases, such as diabetes. Thus, this review intends to show the potential of pearl millet as an alternative food security crop, particularly in countries, like Brazil, where it is not commonly consumed. Also this review presents different processes and products that have been already reported in the literature in order to introduce the great potential of this important small grain to producers and consumers.

1. Introduction

Cereals have been consumed by humans for thousands of years, and they play an important role in our diet as the main source of energy. World cereal production has been increasing by about 1 billion tonnes over the last 50 years; in 2016, production was 29% greater than 2013 (FAOSTAT, 2017). In this scenario, Brazil is the world's sixth largest cereal producer (about 3% of world production), an average of 85 million tonnes in 2016. In that year, the most produced cereal in Brazil were maize (76%), rice (13%), wheat (8%) and sorghum (1%) (FAOSTAT, 2017).

The agricultural production is one of the most vulnerable sectors to climate change (Alexandratos & Bruinsma, 2012). Also, increase in global temperatures, global water deficit, contamination by mycotoxins associated with increasing world population (estimated in 9 billion by 2050) will be responsible for substantial reduction of crop yields resulting in price increase and major food security concerns (Al-Amin & Ahmed, 2016; Khanal & Mishra, 2017). Thus, questions about which crops should be considered to overcome those negative effects are major challenges facing the agribusiness (Daryanto, Wang, & Jacinthe, 2016).

In this context, pearl millet may be an alternative crop that exhibits great advantageous physiological characteristics when compared to other cereals as it is resistant to drought, low soil fertility, high salinity and high temperature tolerance (Rai, Gowda, Reddy, & Sehgal, 2008). These characteristics are due to its extensive root system, which allows effective water and nutrients extraction from deeper soil layers (Netto & Durães, 2005). In addition for being a non-trangenic crop (Dunwell, 2014), millet has a low incidence of mycotoxin contamination compared to other crops, such as wheat and maize (Bandyopadhyay,

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Kumar, & Leslie, 2007; Jurjevic, Wilson, Wilson, & Casper, 2007; Kumar, Basu, & Rajendran, 2008; Ware et al., 2017; Wilson et al., 2006).

Millet, which is a generic term that includes various small grain species belonging to the *Poaceae* family of grasses, has been a food source for humans for more than 10,000 years (Lu et al., 2005; Lu et al., 2009). In 2016, millet stood out as the sixth most produced cereal in the world (28 million tonnes) (FAOSTAT, 2017). However, it is classified as a subsistence crop, and approximately 90% of world production is destined for human consumption in poor regions of Africa and Asia (Council, 1996). One of the major impediment that has restrained the increase of millet production is the scarce economic and technological support provided (Macauley & Ramadjita, 2015). This can be clearly evidenced by observing the world average productivity from the last fifty years, where this crop continues to present the lowest average yield (0.8 t ha^{-1}) when compared to other crops of same botanical family, such as maize (4.0 t ha^{-1}), rice (3.8 t ha^{-1}); wheat (2.6 t ha^{-1}); barley (2.5 t ha^{-1}); rye (2.3 t ha^{-1}); oats (2.1 t ha^{-1}) and sorghum (1.5 t ha^{-1}) (FAOSTAT, 2017b). On the other hand, low productivity is the result of a lack of investment on research genetic programs associated with low use of agronomical techniques, such us fertilizers and mechanization (Macauley & Ramadjita, 2015).

The millet species have different physiological characteristics compared to other cereal crops as they are resistant to drought, low soil fertility, high salinity and high temperatures. These characteristics are due to the extensive root system of these grasses, which allows extraction of water and nutrients from deeper soil layers (Devi, Vijayabharathi, Sathyabama, Malleshi, & Priyadarisini, 2014).

There are several common names of millets: Pearl millet (*Pennisetum glaucum* (L.) R. Br., *Pennisetum typhoides auct. Non (Burm.) Stapf & C.E. Hubbard., Pennisetum americanum* (L.) Leeke, *Pennisetum spicatum* (L.) Körn), Finger Millet (*Eleusine coracana* (L.) Gaertn), Kodo millet (*Paspalum scrobiculatum* L.), Little millet (*Panicum sumatrense* Roth ex Roem. & Schult), Proso Millet (*Panicum miliaceum* (L.), Foxtail millet (*Setaria italica* (L.) P. Beauv.), Barnyard millet Japanese, (*Echinochloa esculenta* (A. Braun) H. Scholz, *Echinochloa frumentacea L.; Echinochloa utilis* Ohwi & Yab.), Browntop millet (*Urochloa ramosa* (L.) Nguyen, *Brachiaria ramosum* (L.) Stapf); Sawa millet (*Echinochloa colona* (L.) Link), White fonio (*Digitaria exilis* (Kippist) Stapf) and Black fonio (*Digitaria iburua* Stapf) (FAO, 1995; USDA,2016a). The Food and Agriculture Organization, FAOSTAT, does not distinguish the production of the different millet species, except pearl millet (*Pennisetum glaucum* (L.) R. Br.) which is the most produced specie; however, in China, foxtail millet is the most relevant (Taylor, 2016).

Pearl millet grains can be processed and consumed as ingredients in diversified foods. They are called "*nutri-cereals*" because of their high protein, fiber, mineral, and fatty acids contents, as well as their antioxidant properties. Also they are an alternative food for celiacs and gluten sensitive individuals (Annor, Marcone, Corredig, Bertoft, & Seetharaman, 2015; Chandrasekara, Naczk, & Shahidi, 2012; Rona et al., 2007; Saleh, Zhang, Chen, & Shen, 2013). Furthermore, the chemical composition of millet grains can promote various health benefits such as reduction of oxidative stress among others (Islam, Manna, & Reddy, 2015; Nani et al., 2015).

Despite its nutritional potential, pearl millet is only used for cereal tillage (vegetable cover for mulch) and feed (grain and forage) in Brazil (Netto & Durães, 2005). The total tillage area in Brazil is around 32 million ha, and pearl millet (*Pennisetum glaucum* (L.) R. Br.) is one of the main cover crops in the Cerrado and the Southern region, in systems of rotation for important commodities, such as soy, maize and cotton (FEBRAPDP, 2012; FEBRAPDP, 2017; Netto & Durães, 2005). Although, millet is not consumed by man in Brazil, this cereal could be considered as an alternative food for human consumption because of its availability, nutritional aspects and also as a source gluten-free food. Thus, this review aims to emphasize the important nutritional and technological potential of pearl millet grains for human consumption, by awakening food industries and consumers to its benefits specially for celiacs and diabetic individuals due to its low glycemic index.

Fig. 1. Pearl millet (*Pennisetum glaucum* (L.) R. Br. cultivar BRS1502) experimental field at Embrapa Maize and Sorghum (Sete Lagoas, MG, Brazil).

2. Pearl millet grain

Pearl millet is an erect grass that has a summer annual cycle of between 75 and 120 days depending on the environmental conditions. Usually, it is of fast growth and reaches an average height of 1.5 to 3 m (Fig. 1). The plant develops compact cylindrical panicles that are 2 to 3 cm wide and 15 to 60 cm long capable of producing between 500 and 2000 seeds per panicle (Durães, Magalhães, & dos Santos, 2003; Taylor, 2016). Its seeds are oval shaped, similar to a pearl, from which it gets its name. The grains are 3 to 4 mm long, and they are significantly larger than other millet species such as: proso, finger, foxtail, kodo and little millet. In general, 1000 seeds of the pearl millet species have an average weight of 8 g, almost three times the weight of proso millet (Durães et al., 2003; FAO, 1995).

This species *Pennisetum glaucum* (L.) R. Br. has many different names around the world. In southern Brazil it is known as *milheto-pérola*, *capim-charuto* and *pasto-italiano,* in the United States, *pearl millet*, *bulrush millet*, *cattail millet*, while in Europe it is called *candle millet* and *dark millet*. In France, it is known as *mil du, Soudan petit mil*, and in Spain and Arabic countries: *mijo perla* and *duhun*, respectively. In addition, in African countries, *P. glaucum* is known as *massago* (Angola), *dagusa* (Ethiopia, língua Amharic), *mhunga* (Zimbabwe), *gero* (Nigéria, língua Hausa), *hegni* (Niger, língua Djerma), *mahangu, sayo* (Mali), *dukhon* (Sudan). In India, it is better known as *bajra, bajrou, sajje* (Taylor, 2016).

3. Uses of pearl millet in Brazil

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) was first introduced to Brazil in 1929 and since then, it has been adapted to the South, Southeast and Center-West regions of the country (Burton, 1972; Kiill, 2005).

Since the 1960s, the research program on *P. glaucum* in Brazil, has focused on improving the agronomic characterization of cultivars that can be used for different purposes, such as: soil cover for no-tillage systems, forage plant, silage or as grains for animal feed (Campelo, Teixeira Neto, & ROCHA, 1998; Guimarães Junior, Gonçalves, & Rodrigues, 2009; Santos et al., 2017).

The practice of no-tillage is used to increase agricultural productivity and to control soil erosion, while at the same time it reduces compaction and improves nutrient availability in the soil (Campelo et al., 1998). Pearl millet has a fast growth rate, a deep root system and a good production of green mass. The no-tillage system uses plant residues from decomposed straw as a soil cover improving the productivity of commodities such as soy and cotton, due to a reduction of soil temperatures, a slow release of nutrients and improved water retention in the soil (Netto & Durães, 2005). Although, there is no official production data in Brazil, the estimated planted area of pearl millet (*Pennisetum glaucum* (L.) R. Br.) is 5 million ha.

In addition, factors such as nutritional composition and low production costs of pearl millet grains (half the price of maize) have motivated studies for replacing maize with pearl millet in animal feed (Alonso et al., 2017; Bergamaschine et al., 2011). According to Rodrigues et al. (2001), the substitution of maize for pearl millet in animal feed may have advantages, such as higher protein content, lower incidence of mycotoxins and similar lipid content.

4. Nutritional quality of pearl millet grains

In recent years, there has been an increase of products based on whole grains because they contain a higher content of dietary fiber, micronutrients and bioactive compounds (Gong et al., 2018). Pearl millet grains can be considered a possible alternative for food diversification because they have the fibers, minerals, proteins and antioxidants with similar or even higher levels than those found in traditional grains such as rice and maize (Saldivar, 2003; Taylor, 2016). The chemical composition of pearl millet along with other traditional cereal crops is given in Table 1. The chemical composition of pearl millet (dry basis) is, on average, 72.2% carbohydrate, 11.8% protein, 6.4% lipid, 7.8% dietary fiber and 1.8% minerals (Table 1). However, variations of these levels are possible due to genotype, climatic conditions, soil nutrient content and type of processing.

4.1. Carbohydrates

Carbohydrates are the main components of cereals and are mostly starch, followed by fibers. The average content of carbohydrates in pearl millet grains was 72.2%, which is lower than rice (84.9%), maize (78.1%) and higher than wheat (68.8%) (Table 1). The average dietary fiber content in pearl millet grains was 7.8% (Table 1). This value was higher than rice (3.5%) although, similar to maize (8.1%). On the other hand, it has lower fiber content when compared to rye (16.8%), barley (14.5%) and oats (11.8%) (Table 1). Consumption of food sources with fiber should be stimulated as they promote quality of life (Chuang et al., 2012), reduce symptoms of depression (Miki et al., 2016), reduce incidences of inflammatory bowel diseases (Liu, Wu, Li, & Zhang, 2015) and heart problems (Kim & Je, 2016).

Table 2
Amino acid composition of cereal grains.[a]

Amino acids (g/100 g protein)	Pearl millet[a]	Maize	Wheat	Sorghum	Rye	Barley	Rice	Oat
Leucine	10.7	12.3	6.8	12.9	5.4	6.8	8.2	7.6
Isoleucine	4.4	3.6	3.3	3.7	2.0	3.6	4.1	4.1
Valine	4.9	5.1	4.3	4.6	3.0	4.9	5.8	5.5
Threonine	4.0	3.8	2.8	3.7	2.8	3.4	3.5	3.4
Arginine	4.6	4.9	4.9	3.9	4.4	5.0	8.7	7.1
Lysine	3.1	2.8	2.7	2.1	2.8	3.7	3.5	4.1
Methionine	1.1	2.1	1.7	1.7	1.5	1.9	2.4	1.8
Cisteine	1.5	1.8	2.0	1.9	na	2.0	1.8	2.4
Tryptophan	1.4	0.7	1.3	1.2	1.0	1.7	1.2	1.4
Glutamic Acid	23.0	18.8	32.8	20.6	22.2	26.1	18.4	21.9
Alanine	8.7	7.5	3.7	8.9	3.9	3.9	5.6	5.2
Proline	5.8	8.7	15.7	7.7	7.8	11.9	4.7	5.5
Aspartic Acid	8.5	6.9	5.5	6.6	5.4	6.2	9.2	8.6
Phenylalanine	4.4	4.9	5.2	5.2	4.2	5.6	5.3	5.3
Tyrosine	3.0	4.1	2.1	2.7	1.9	2.9	5.3	3.4
Histidine	2.3	3.0	2.7	1.9	1.8	2.2	2.5	2.4
Glycine	2.7	4.1	4.3	3.7	4.0	3.6	4.5	4.9
Serine	5.2	4.7	4.7	4.9	4.4	4.2	5.2	4.4

Other cereals source: USDA, 2016b
na = no analyzed.
[a] Range of values data from: Adebiyi, Obadina, Adebo, & Kayitesi, 2017; Osman, 2011; Saldivar, 2003; Taylor, 2016.

4.2. Proteins and amino acids

Proteins are the second major component in pearl millet grains. The grains contain 11.8% protein, similar to sorghum (10.7%) and higher than maize (9.2%) and rice (8.6%) (Table 1). However, pearl millet has a lower protein content compared to oats (16.7%), wheat (14.0%) and rye (13%) (Table 1). Oscillations in the protein content of cereals are observed in different research projects, because they are directly related to factors such as: genotypic characteristics, soil moisture content and use of nitrogen fertilizers (FAO, 1995).

The composition of amino acids of pearl millet compared to other traditional cereal crops is shown in Table 2. Pearl millet protein amino acid composition has on average high levels of glutamic acid (23 g/100 g protein), but lower than wheat and barley. Glutamic acid is a nonessential amino acid known to be a neurotransmitter or precursor of γ-aminobutyric acid (GABA) (Han, Kim, Yang, Jeong, & Kim, 2015). Foods rich in glutamic acid may prove to be beneficial to health and according to Han et al. (2015) glutamic acid supplementation may be considered an alternative therapy to reduce the symptoms of menopause, as it (glutamic acid) may attenuate the estrogen deficiency at this period.Furthermore, GABA is associated to several physiological,

Table 1
Nutritional composition of cereals.[a]

Proximate composition (g/100 g)	Pearl millet	Maize	Wheat	Sorghum	Rye	Barley	Rice	Oat
Carbohydrate	69.4–76.1 (72.2)	69.4–85.1 (78.1)	67.7–69.3 (68.8)	72.2–77.1 (74.6)	64.7–67.7 (66.4)	63.4–73.3 (68.2)	81.9–88,2 (84.9)	60.6–62.9 (61.4)
Protein	9.7–14.5 (11.8)	7.7–12.1 (9.2)	13.2–14.8 (14.0)	9.4–11.8 (10.7)	11.6–14.0 (13.0)	11.5–15.3 (12.9)	6.7–11.0 (8.6)	14.9–17.1 (16.7)
Lipid	5.1–9.5 (6.4)	1.9–4.3 (3.3)	1.5–2.8 (2.2)	3.2–3.7 (3.4)	1.8–2.0 (1.9)	1.8–2.7 (2.2)	1.6–2.2 (2.1)	6.4–8.6 (7.6)
Dietary Fiber	7.0–8.5[b] (7.8)	4.5–8.2 (8.1)	11.9–15.1 (13.1)	7.3–11.8 (9.6)	16.1–17.4 (16.8)	11.5–16.7 (14.5)	2.7–4.7 (3.5)	11.2–12.5 (11.8)
Ash	0.8–2.5 (1.8)	0.7–1.8 (1.3)	1.8–2.0 (1.9)	1.5–1.8 (1.7)	1.7–2.0 (1.9)	1.5–2.9 (2.2)	0.6–1.4 (0.9)	1.4–3.6 (2.5)

The other data correspond to the range found in the following sources, for pearl millet: Gull, Prasad, & Kumar, 2015; Obadina et al., 2016; Saldivar, 2003; Siroha et al., 2016 and Taylor, 2016. For the other cereals: Butt, Tahir-Nadeem, Khan, Shabir, & Butt, 2008; Prasad, Hymavathi, Babu, & Longvah, 2018; Saldivar, 2003; TACO, 2011; TBCA, 2017; USDA, 2016b.
[a] All values are expressed on dry matter basis. The lower number indicates the average value and upper refers to the range of values.
[b] Range of Dietary fiber from the following sources: Saldivar, 2003 and Taylor, 2016.

nutritional and food ingredient functions (Sharma, Saxena, & Riar, 2018).

Moreover, pearl millet has higher content of essential amino acids (leucine (10.7 g/100 g protein) and isoleucine (4.4 g/100 g protein)) than wheat, rice and oats. However, it is the cereal that has the lowest concentration of methionine (1.1 g/100 g protein) (Table 2).

According to FAO (1995) the quality of protein in pearl millet grains satisfies the nutritional requirements of an adult, but does not meet the protein needs of infants and children, due to the amount of essential amino acids, especially lysine, which is usually low in cereals. Nevertheless, the lysine content of pearl millet (3.1 g/100 g protein) is relatively higher than maize, rye, wheat and sorghum (Table 2). This is possibly a consequence of the large germ of pearl millet with a relatively high proportion of albumin and lysine-rich globulins (Taylor, 2016).

4.3. Fats

Pearl millet grain has high lipid content because the germ represents ~ 21% of the whole grain (Taylor & Emmambux, 2008). However, the high lipid content of this species may promote negative effects on the stability of products such as flours, because unsaturated fatty acids are susceptible to oxidation (Tiwari, Jha, Pal, Sethi, & Krishan, 2014). On the other hand, the presence of unsaturated fatty acids may be beneficial. According to Annor et al. (2015), the composition of fatty acids (quantification and type) present in each species of millet is directly related to the hypoglycemic properties of this cereal. According to Taylor (2016) and Annor et al. (2015) the major fatty acids of pearl millet grain are linoleic acid (C18:2), typically 39–45%; oleic acid (C18:1), 21–27%; and palmitic acid (C16:0), 20–21%.

The lipid content of pearl millet grains is very high (6.4%), almost twice the amount in sorghum (3.4%) and maize (3.3%), but lower than oats (7.6%) (Table 1). However, variations can be found and result in different comparisons to that observed above; for example Belton and Taylor (2002) found that some pearl millet cultivars have lower lipid contents than maize.

4.4. Minerals

The total ash content of pearl millet (1.8%) is similar to wheat (1.9%), higher than maize (1.3%) and rice (0.9%) and lower than oats (2.5%) and barley (2.2%). Regarding mineral composition, phosphorus (~3.338 mg/kg dry basis), potassium (~3.932 mg/kg dry basis) and magnesium (~1.333 mg/kg dry basis) are found in considerable quantities, while minerals such as calcium (~300 mg/kg dry basis), iron (~ 18 mg/kg dry basis) and zinc (~43 mg/kg dry basis) are in much lower quantities (Ragaee, Abdel-Aal, & Noaman, 2006; Saldivar, 2003; Taylor, 2016). Due to the low content of zinc and iron, some research programs have concentrated efforts on promoting biofortification of pearl millet (Ullah et al., 2016).

4.5. Bioactive compounds

Studies have demonstrated that whole grain millet and its bran are rich sources of phenolic compounds (phenolic acids and flavonoids) and a source of natural antioxidants (Chandrasekara et al., 2012; Chandrasekara & Shahidi, 2011a, 2011b, 2011c). According to the above mentioned works, these compounds, which are secondary products of plant metabolism, have antioxidant capacities and are associated to reduced risk of chronic diseases related to oxidative stress. Pearl millet grains have low concentrations of benzoic acid derivatives (hydroxybenzoic acid, gallic acid, *p*-hydroxybenzoic, vanillic, syringic and protocatechuic), but high levels of cinnamic acid derivatives (hydroxycinnamic, coumaric, ferulic, sinapic) (Chandrasekara & Shahidi, 2011a; Taylor & Duodu, 2015). Nani et al. (2015) reported that pearl millet contained gallic acid (15.3 μg/g), syringic acid (7.4 μg/g), *p*-coumaric (1350 μg/g) and ferulic acid (199 μg/g).

When comparing the quantities of phenolic acids with other cereals, N'Dri et al. (2013) found that pearl millet presented higher amounts (64.8 mg/kg) of phenolic acids than sorghum (27.3 mg/kg). Dykes and Rooney (2007) observed that pearl millet had 1478 μg/g, which was higher than that found in rye (1366 μg/g), barley (1346 μg/g), wheat (1342 μg/g), sorghum (746 μg/g), maize (601 μg/g) and oats (472 μg/g). Among the phenolic acids, ferulic and *p*-coumaric acids are predominant in pearl millet grains, according to Chandrasekara and Shahidi (2011b) and N'dri et al. (2013). In general, phenolics are not distributed evenly in the grain, these compounds are mainly found in the pericarp so the most beneficial form to consume pearl millet is as whole grain or bran (Chandrasekara & Shahidi, 2011b).

When comparing the antioxidant capacity of five whole grains, wheat (*Triticum aestivum* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), rice (*Oryza sativa*), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), Prajapati, Patel, Parekh, and Subhash (2013) found that pearl millet grains had the most phenolic compounds and the highest antioxidant activity. According to Nani et al. (2015) phenolic compounds found in whole grains have immunosuppressive effects and can be used as dietary supplements for the treatment of autoimmune diseases.

4.6. Antinutritional factors

The main antinutritional compounds found in pearl millet are phytic acid and C-glycosylflavones, such as apigenin, glucosylvitexin, glucosylorientin and vitexin (Taylor, 2016). Phytic acid is a natural antioxidant present in most cereals that inhibits oxidation reactions of the seeds and retains inorganic phosphorus when consumed. However, from the nutritional point of view, high consumption of these compounds may lead to a reduction in the bioavailability of minerals, such as zinc, calcium and manganese, due to the chelating capacity of bivalent minerals (Gupta, Gangoliya, & Singh, 2015). In addition, the presence of phytic acid in cereals may promote the reduction of protein digestibility by inhibiting the action of protease enzymes in the digestive tract. According to García-Estepa, Guerra-Hernández, and García-Villanova (1999) the phytic acid content of millet grains resembles cereals such as maize and sorghum, and is higher than oats, rice, barley, rye and wheat. According to various authors, pearl millet levels of phytic acid can vary from 588 mg/100 g to 1382 mg/100 g (El Hag, El Tinay, & Yousif, 2002; Gabaza, Shumoy, Muchuweti, Vandamme, & Raes, 2017).

Flavones are a subclass of flavonoids belonging to phenolic compounds that are synthesized by the plant through the stimulus of light and responsible for the yellow pigmentation of *P. glaucum* (Reichert, 1979). Although, luteolin, a flavone present in millets, have antioxidant properties, other studies have shown evidence that the presence of C-glycosylflavones in foods may promote the inhibition of thyroid peroxidase (TPO), an enzyme produced in the thyroid gland responsible for the production of thyroid hormones (Gaitan et al., 1989; Mezzomo & Nadal, 2016).

Gaitan et al. (1989) evaluated the anti-thyroid and goitrogenic effect of pearl millet grains. They observed that rats fed with *Pennisetum glaucum* (L.) R. Br. meal showed a significant reduction in thyroid hormone production, suggesting that high concentrations of C-glycosylflavones (1,020 mg/kg) in particular, glucosylvitexin, glucosylorientin and vitexin were responsible for the result. However, due to scarce studies, it is still unclear how much intake is necessary to promote similar effects in humans. Thus, it is suggested that, grains of pearl millet are submitted to processing promoting the reduction of antinutritional factors for the safe consumption of the grain (Brahmbhatt, Fearnley, Brahmbhatt, Eastman, & Boyages, 2001).

Table 3
Effect of processing on pearl millets.

Process	Processing effects	References
Cooking	Reduction of antinutritional factors	Jha, Krishnan, and Meera (2015)
	Reduction of antioxidant capacity	Chandrasekara et al. (2012); N'Dri et al. (2013)
	Reduction of phenolic compounds	Hithamani and Srinivasan (2014)
	Increase of antioxidant capacity	Prajapati et al. (2013)
	Increase of zinc bioaccessibility	Jha et al. (2015)
Milling	Reduction of flour shelf life	Bhati et al. (2016)
	Increase of free fatty acid content	Tiwari et al. (2014)
Decortication	Reduction of antioxidant potential	Chandrasekara et al. (2012), Chandrasekara and Shahidi (2011b)
	Reduction of fiber, iron and zinc content	Hama et al. (2011)
	Reduction of phytic acid content and phenolic compounds	Chandrasekara et al. (2012); Hama et al. (2011)
	Reduction of insoluble fiber, amino acids and lipids	Serna-Saldivar, Clegg, and Rooney (1994)
	Increase of starch and protein digestibility	
Roasting	Reduction of essential amino acids content	Obadina et al. (2016)
	Reduction of phytic acid content and free fatty acids	Jalgaonkar, Jha, and Sharma (2016)
	Increase of bioaccessibility of phenolics	Hithamani and Srinivasan (2014)
	Increase of phenolic acid content	
Acid treatment	Reduction of c-glycosylflavones and grain color modification	Reichert (1979)
	Reduction of free fatty acid content	Bhati et al. (2016)
	Increase of iron bioavailability	
Blanching	Reduction of free fatty acid content	Bhati et al. (2016); Kadlag, Chavan, and Kachare (1995)
	Reduction of the rancidity	Nantanga, Seetharaman, de Kock, & Taylor, 2008
	Increase of flour shelf life	Nantanga et al., 2008; Kadlag et al. (1995)
	Increase of iron availability *in vitro*	Bhati et al. (2016)
Extrusion	Reduction of antioxidant capacity	N'Dri et al. (2013)
	Reduction of antinutritional factors	Balasubramanian et al. (2014); Sihag, Sharma, Goyal, Arora, and Singh (2015)
	Increase of protein digestibility	Almeida-Dominguez et al. (1993)
	Increase of solubility and cold paste viscosity	
Popping	Increase of starch digestibility *in vitro*	Muralikrishna, Malleshi, Desikachar, and Tharanathan (1986)
	Reduction of grain density	Singh and Sehgal (2008)
Germination	Reduction of phenolic compounds	Nithy, Ramachandramurty,& Krishnamoorthy (2007).
	Reduction of antinutritional factors	Badau, Nkama, and Jideani (2005); Sihag et al. (2015); Tou et al., 2006
	Increase of protein digestibility	Nkama et al. (2015)
	Increase of free amino acid content	Elyas, El Tinay, Yousif, and Elsheikh (2002)
	Increase all the essential amino acids content	Adebiyi et al., 2017
	Increase of mineral composition	
	Increase of solubility	Akinola, Badejo, Osundahunsi, and Edema (2017)
Fermentation	Increase of product acidity,	Khetarpaul and Chauhan (1990a), (Khetarpaul & Chauhan, 1990b)
	Reduction of phytic acid	Elyas et al. (2002); Gabaza et al. (2017); Tiwari et al. (2014)
	Reduction of phenolic compounds	Elyas et al. (2002)
	Reduction of minerals (Na, K, Mg, Cu, Fe, Mn and Zn)	Tiwari et al. (2014)
	Increase of bioactive compounds content	Salar, Purewal, and Sandhu (2017), Gabaza et al. (2017)
	Increase of protein digestibility	Ali, El Tinay, and Abdalla (2003)
	Increase of mineral composition and amino acid content	Adebiyi et al. (2017)
	Increase of paste viscosity properties	Akinola et al. (2017)

5. Grain processing and effects

The post-harvest millet process starts with the separation of the grains from the panicle, removal of soils, such as stones and sands followed by debranning. Wholemeal products do not require debranning. Subsequently the grains can be submitted to different secondary processes, such as physical (milling, decortication, cooking, roasting, blanching, extrusion and popping), chemical (acid treatment) and biological processes (fermentation, germination), for elaboration of diversified food products. Table 3 shows the effects of these processes commonly applied to millet grains, as well as their respective effects.

Grain cooking, milling and decortication, are the most common processes used on millet, because they are simple and inexpensive, that can be applied as pre-treatment. Pearl millet grains (whole or decorticated) can be cooked similarly to "rice" either by open-pan boiling or pressure cooking and even in microwave oven (Taylor, Barrion, & Rooney, 2010). Milling is used to produce pearl millet flours with different particle size distribution, but it causes the release of fatty acids present in the germ prone to oxidation hence reducing flour shelf-life (Tiwari et al., 2014). Decortication can be used to obtained light colored grains with better palatability, taste and texture. It promotes changes in grain color by removing the bran, which in turn reduces flavonoids content up to 50%. The flavonoids are responsible for the grayish pigmentation (Akingbala, 1991). However, due pearl millet germ is embedded in the endosperm, decortication is not effective and more efforts are still needed to develop techniques to remove the pericarp and germ without causing significant reduction of grain endosperm (Hama et al., 2011).

Roasting, acid and blanching treatments are applied to pearl millet grains to modify their color, to reduce antinutritional factors and to promote the inactivation of lipases, that are responsible for the rancid odor when grain is milled, thus product shelf life is improved (Bhati, Bhatnagar, & Acharya, 2016). In the roasting process, grains or flours are exposed to heat in the dry condition, where temperatures may vary from 120 to 180 °C for 75 to 120 min. Acid treatment requires the preparation of various types of acid solutions, such as acetic acid, tartaric acid or diluted HCl, whereas in blanching, the grains are immersed in water at ~ 100 °C for 10 to 90 s.

Extrusion cooking and popping are thermo-physical processes still to be explored with great potential to be introduced given the commercial opportunity. Extrusion requires considerable investment, which may restrict its use. Apart from economic issue, extrusion of pearl millet grain presents certain challenges, due to its high concentration of lipids and fibers. However, some authors have reported that pearl millet has great potential to be used to develop extruded products with better digestibility and also improved sensory acceptance (Balasubramanian, Kaur, & Singh, 2014). Unlike extrusion, popping is a simple and inexpensive technique, but few studies have been reported this process

(Table 3). A possible explanation is due to grain characteristics, since its grain has a fine pericarp and farinaceous endosperm, factors that do not contribute to a good expansion performance (Hadimani, Muralikrishna, Tharanathan, & Malleshi, 2001; Mishra, Joshi, & Panda, 2014). Nevertheless, this disadvantage could be a motivation for promoting research programs to improve pearl millet germplasm aiming to improve grain the expansion properties and diversified pearl millet genotypes (Kumari et al., 2015).

Biologycal processes, like germination and fermentation are *household* practice commonly in African and Asia countries which promotes physicochemical alterations (Table 3). In general, the germination process is carried out in three stages: immersion in water (~ 8 h), germination (24–28 °C/ 24–48 h) and drying (~50 °C) (Taylor, 2016). The fermentation is carried out by immersing the grains in water at room temperature from 2 to 4 days. The grain fermentation can be accomplished either by the addition of starter cultures, which improves process control and standardization of the final product or by spontaneous fermentation *via* natural microbiota, like lactic bacteria (*Lactobacillus fermentum, Lactobacillus plantarum* and *Pediococus pentosaceus*), yeast (*Saccharomyces cerevisiae, Candida kruse*) and/or molds (*Mucor circinelloides, Rhizopus microsporus*) (Franz et al., 2014).

In addition, emerging technologies such as irradiation can be also applied to pearl millet grains, but scarce studies have been reported in the literature. According to Mohamed, Ali, Ahmed, Ahmed, and Babiker (2010) irradiation up to 2 kGy can be applied to pearl millet meal, as an alternative to thermal and chemical treatments to increase shelf-life and to reduce the incidence of the bitter taste during flour storage. Even lower exposure of 0.5 kGy radiation promotes significant reduction of fungal growth and phytic acid content.

Due to the fact that millet is not a commercial and popular grain worldwide, the application of other emerging technologies, such as ohmic heating, pulsed electric field, cold plasma and microwave have not been reported in the literature yet. It is envisaged the use of these techniques in millet grains may be promising, as these techniques have been studied with other cereals with potential of being commercially used (Altan, 2014; Ménera-López, Gaytán-Martínez, Reyes-Vega, Morales-Sanchez, & Figueroa, 2013; Qian, Gu, Jiang, & Chen, 2014; Thirumdas, Saragapani, Ajinkya, Deshmukh, & Annapure, 2016).

6. Health promoting properties

Pearl millet grains have several functional properties, due to their high fiber content, fatty acid composition and phytochemical compounds (Annor et al., 2015; Patel, 2015). In addition to its anti-inflammatory, antihypertensive, anticarcinogenic characteristics, and the presence of antioxidant compounds, pearl millet also helps to reduce the risk of heart diseases, inflammatory bowel disease and atherosclerosis (Chandrasekara & Shahidi, 2011a, 2011b; Romier, Schneider, Larondelle, & During, 2009).

Pearl millet grains are naturally gluten-free, an advantage considering that the intake of gluten protein, particularly found in wheat, may promote several metabolic disorders in certain individuals, causing allergies, intolerances, autoimmune diseases and intestinal permeability (Czaja-Bulsa, 2015; Hollon et al., 2015). Therefore, pearl millet may prove to be a low-cost functional alternative for celiacs, people with non-celiac gluten sensitivity (NCGS), gluten sensitivity patients (GS) and food style adepts. The acquired knowledge of pearl millet health benefits is of great importance that should be considered in nutritional programs.

6.1. Hypoglycemic properties

According to the World Health Organization (WHO) type 2 diabetes has increased in children and adults worldwide, and is now the 6th cause of death in the world (WHO, 2017a). In Brazil, this disease affects 9 million people, and is classified as the 4th largest cause of death in the country (Portal Brasil Saúde, 2015; WHO & UNpartners, 2015).

In general, diabetes can be triggered due to genetic pre-dispositions, obesity and high consumption of foods with a high glycemic index. According to Nani, Brixi-Gormat, Bendimred-Hmimed, Benammar, and Belarbi (2012) and Ugare, Chimmad, Naik, Bharati, and Itagi (2014) the use of millet grains to develop new products can help prevent the risk of diabetes, due to their low glycemic levels.

Nani et al. (2012) evaluated the effect of the consumption of pearl millet (*Pennisetum glaucum* (*L.*). R. Br.) on the glucose metabolism of diabetic rats. The authors concluded that the consumption of pearl millet meal may be useful to correct hyperglycemia caused by type 2 diabetes, and therefore reduce the intensity of the disease, that can be an alternative to prevention. Hegde, Rajasekaran, and Chandra (2005) observed that animals consuming a feed with 55% kodo millet meal resulted in a reduction of 42% hyperglycemia, 27% of cholesterol and increased levels of enzymatic antioxidants (GSH, vitamin E and C) and non-enzymatic (glutathione reductase).

According to Annor, Tyl, Marcone, Ragaee, and Marti (2017), millet grains have higher slowly digestible starch than other cereals, which was atributed to starch characteristics, such as, amylose content, granular structure (polygonal format with porous surfaces), amount and type of fatty acids (oleic acid content) capable of forming complexes with starch molecules, the starch-protein-lipid interactions and high content of fibers. Furthermore, the presence of phytochemicals (phenolic acids, flavonoids and phytates) may contribute to inhibit the action of gastrointestinal α-amylase (pancreatic) and α-glycosidase (intestinal) enzymes that hydrolyze starch, oligosaccharides and disaccharides to monosaccharides, thus reducing body hyperglycemia (Cao & Chen, 2012; Kim, Hyun, & Kim, 2011; Shobana, Sreerama, & Malleshi, 2009; Shukla & Srivastava, 2014). However, the hypoglycemic nature of millets can be significantly affected by the type of processing applied to them, hence the adoption of processes that maintain low starch hydrolysis should be encouraged (Annor et al., 2017).

6.2. Anticancer properties

Cancer is the second largest cause of global death, with around 8.8 million deaths in 2015. The types of cancers that kill most are: lung (1.69 million); liver (788,000); colorectal (774,000); stomach (754,000) and breast (571,000 deaths) (WHO, 2017b). Although the disease is related to different factors such as genetic predisposition; smoking, obesity, chronic inflammation, age, immunosuppression and radiation, research shows that the choice of food that is consumed during life may also influence the predisposition to develop this disease (National Cancer Institute, 2015).

Countries such as India, Burkano Faso and Nigeria where the base diet is small cereal grains, mainly millet, there is a low incidence of cancer compared to countries that are based on cereals such as corn and wheat (Chen, Cole, Mi, & Xing, 1993; van Rensburg, 1981; WHO & UNpartners, 2015). Some medical studies have suggested that peptides, proteins and phenolic acids found in millet grains may be promising in the prevention and treatment of cancer (Shan et al., 2014; Shan et al., 2015; Srikanth & Chen, 2016).

According to Chandrasekara and Shahidi (2011a) phenolic acids such as ferulic and *p*-coumaric, found in whole pearl millet (*Pennisetum glaucum* (L.) R. Br.), have the capacity to reduce HT29 tumor cells. Nishizawa et al. (2002) reported a reduction in the proliferation of hepatic inflammatory cells in rats fed a 20% protein proso millet diet (*Panicum miliaceum* L). In a similar research, Zhang, Liu, and Niu (2014) observed that proso millet grains also have antiproliferative activity *in vitro* against human liver cancer cells. Shan et al. (2014) and Shan et al. (2015) found that millet bran-derived peroxidase from foxtail millet (*Setaria italica*), has a potential therapeutic use to treat rectal colon cancer, due to its strong inhibitory power on preventing cancer cells from growing in *in vitro* and *in vivo* tests.

Table 4
Products made with pearl millet.

Product	Country	Ingredients	Main conclusions	Reference
Fura balls[a]	Nigeria	Extruded pearl millet-soybean flours blends, black pepper and ginger	- The extrusion of the millet-soybean blends promoted increase of shelf-life and increase in protein content of the product; - The maximum proportion of soybean meal added should be 38.5% for sensorial acceptance.	Filli et al. (2013)
Ben-saalga[a] (porridge)	Burkina Faso	Pearl millet flour, groundnuts, malted barley flour, sugar, ginger and mint.	- The addition of the groundnuts and malted barley flour, enabled a porridge with the appropriate balance of macronutrients and high energy density at a suitable consistency.	Tou et al. (2007)
Chapati[a] (flat-bread)	India	Pearl millet flour and water	- Chapatti making resulted in decrease of antioxidant properties, when compared to its raw flour.	Siroha et al. (2016)
Ladoo[a] (sweet)	India	Popped pearl millet, roasted and dehusked groundnut, roasted and dehusked chickpea, jaggery and water	- Popped pearl millet can be successfully used for the preparation of *ladoo*, reducing cost and increasing *in vitro* protein digestibility.	Singh and Sehgal (2008)
Dakuwa[a] (sweet)	Nigeria	Malted pearl millet flour, groundnut, ginger, hot pepper and honey	- The malting of grains improved the apparent protein digestibility without affecting the sensorial aspects such as texture and taste.	Nkama et al. (2015)
Ready-to-eat snack	India	Whole pearl millet, finger millet and decorticated soy bean blended extruded	- The pearl millet expanded in a twin screw extruder, presented a light color, and promising characteristics for the production of low cost extrudates.	Balasubramani-an et al. (2012)
Weaning food	India	Malted and extruded millet flour (MEMF), extruded millet flour (EPMF), extruded barley flour (EBF), malted and extruded barley flour (MEBF), skim milk powder (WPC), sugar and vegetable oil (VO)	- The mixture that resulted in the best physical and sensorial characteristics was EBF (20.99%), EPMF (20.77%), MEFE (7.39%), MEBF(6.53%), WPC (5%), sugar (6%) and vegetable oil (4 mL); - The use of pearl millet and barley showed great potential for replacing rice and wheat, including at a low cost and with a highly nutritious product.	Balasubramani-an et al. (2014)
Non-dairy Probiotic Beverage	India	Germinated pearl millet, wheat, barley flour; oat meal, guar gum, sugar cardamom and probiotic culture (*Lactobacillus acidophilus* NCDC14) in 50:50 soy/H_20.	- There was a linear increase in probiotic count with an increase in pearl millet flour in the beverage; - The authors suggested that in order to obtain better sensory acceptance the addition of pearl millet flour should be limited to 4 g/ 100 mL.	Mridula et al. (2015)
Biscuits	South Africa	Fermented or raw whole millet flours, defatted soy flour, sugar, margarine and water	- The pearl millet biscuits are nutritious, resembling the texture of commercial wheat cream crackers, but they differ in their pronounced flavor; - The authors suggested that the consumption of these biscuits has the potential of being a supplementary food for school-age children in Africa.	Omoba, Taylor, and Kock (2015)
	Nigeria	Germinated and fermented pearl millet flours, sugar, sunflower oil, vanilla extract, yeast and water	- The use of germinated and fermented flours results in higher nutritional quality and lower bulk density; - Sprouted and fermented pearl millet flour are potential ingredients for baking products.	Adebiyi, Obadina, Mulaba-Bafubiandi, et al. (2016)
Pastas	India	Durum wheat semolina (DWS), pearl millet flour (PMF), finger millet flour (FMF) and carrot pomace powder (CPP)	- The pearl millet pasta showed greater loss of solids, reduction of weight gain and firmness, but presented a higher nutritional value; - Desirable physical characteristics of pasta was obtained with 46% DWS, 30% PMF, 20% FMF and 4% CPP.	Gull et al. (2015)
	India	Depigmented pearl millet flour, chickpea flour and water.	- The authors suggested depigmentation of pearl millet grains by acid treatment or bleaching, in order to obtain clearer pasta that improves its acceptability.	Rathi, Kawatra, and Sehgal (2004)
	India	Pearl millet flour (PMF) and wheat semolina (WS).	- PMF increased the protein content significantly, however the hardness, cohesion and elasticity decreased; - WS: PMF (70:30) was good for making pasta with desirable quality.	Jalgaonkar and Jha (2016)
Breads	Nigeria	Pearl millet flour (PMF), kidney beans, tigernut and xanthan gum	- Composite flour with 85% of PMF is a viable alternative to 100% wheat flour replacement in bread production.	Awolu (2017)
	India	Wheat flour, pearl millet flour, yeast, sodium chloride and water	- The results showed that pearl millet flour had excellent emulsifying properties; - Addition of 5% of pearl millet flour is able to improve the rheological properties of the dough, as well as the specific volume and texture of the bread.	Maktouf et al. (2016)
Kibbeh gluten free	Brazil	Mixed meat, pearl millet flour roasted, soybean oil, salt, fresh mint; fresh parsley and fresh garlic.	- The kibbeh showed good acceptability not differing significantly from whole wheat flour samples for overall appearance, texture and taste; - Pearl millet flour can be used as a substitute for wheat flour for formulations intended for the celiac public because of their nutritional quality, sensorial and stability after freezing.	Brasil et al. (2015)

[a] Traditional local foods of pearl millet.

However, grain functionality is directly linked to the type of processing applied to it. According to Chandrasekara and Shahidi (2011a) decorticated pearl millet grains have lower anticarcinogenic activity than whole grains. Sharma, Saxena, and Riar (2016) observed that germinated grains of barnyard millet (*Echinochloa frumentaceae*) are more functional because they have a higher phenolic acid content and gamma-amino butyric acid (GABA), an amino acid that promotes health benefits such as mood enhancement and inhibition of developing cancer cells.

6.3. Probiotic and prebiotic properties

Prebiotics are non-digestible food ingredients that when consumed promote growth and maintenance of probiotics, microorganisms belonging to intestinal microflora, which are related to health benefits of the host (Farooq, Mohsin, Liu, & Zhang, 2013). The consumption of foods that contain prebiotics and probiotics is recommended in order to promote the improvement of the immune and physiological systems, as well as the reduction of inflammatory bowel diseases, antimicrobial action and reduction of allergic diseases (Benítez-Páez et al., 2016; Sandhu et al., 2017). The potential of fibers as prebiotic and the

Fig. 2. Traditional local foods made from pearl millet. a) *Fura*, Nigeria; b) *Porridge*, Nigeria; c) *Ladoo*, India.

probiotic strains of fermented pearl millet have also been studied (Palaniswamy & Govindaswamy, 2016; Pedersen, Owusu-Kwarteng, Thorsen, & Jespersen, 2012).

According to Farooq et al. (2013), fibers in pearl millet grains have a prebiotic effect *in vitro*, resulting in the growth of probiotic cultures such as *Lactobacillus rhamnosus* and *Bifidobacterium bifidus*. The authors also observed enhancement of short chain fatty acids (SCFA), metabolic products of fermentation, known to regulate physiological processes. They suggested that millet dietary fiber has a potential for being used in formulation of new nutraceuticals.

In relation of probiotic strains isolated from fermented millet products, Pedersen et al. (2012) identified potential probiotic yeasts (*Trichosporon asahii*) in *Fura*, a spontaneously fermented product made from pearl millet grains. Owusu-Kwarteng, Tano-Debrah, Akabanda, and Jespersen (2015) reported that *Lactobacillus fermentum* strains isolated from fermented pearl millet grains presented antimicrobial activity against *Listeria monocytogenes* and *Staphylococcus aureus*. In other research, Nduti et al. (2016) isolated strains of *Lactobacillus* in *Kimere*, a fermented millet-based food, that was inoculated in yoghurts and distributed to needy children in Kenya. The authors observed that the consumption of 200 mL for 7 days of the probiotic yoghurt promoted reduction of aflatoxin intoxication.

7. Foods and beverages products of pearl millet

In Africa and India, pearl millet grains are used to produce a wide variety of traditional local foods, such as porridges, flatbreads, couscous, sweets, alcoholic beverages (*opaque beer or Dogon millet beer, chibuku shake, mbeg, merissa*) and non-alcoholic drink (*pombe, pito, boza, kunun Zaki, bushera, mahewu, oskikundu, marewa*) (Adebiyi, Obadina, Adebo, & Kayitesi, 2018). Most of these products are produced in *household* or in small production units consumed in the main meals. However, few studies have been reported the nutritional and sensory aspects of these products. In addition, due to the vast number of different local variations, this research will be limited on describing few examples of food preparations available in international literature with pearl millet, that are displayed in Table 4.

Fura, a short shelf-life made in ball format (Fig. 2a) obtained from cooking a mixture of fermented and non-fermented pearl millet flour and spices is widely consumed in Nigeria (Adebiyi, Obadina, Adebo, & Kayitesi, 2018). Depending on the region, it is consumed with yoghurt ("*nono*") or mashed in water before consumption as porridge (Filli, Nkama, Jideani, & Ibok, 2013).

Porridges (*ben-saalga, uji, ugali, oko, tõ, obushera, koko*, *bogobe, tchobal, bouillie* and *kambu koozh*) may be prepared from pearl millet flour as fermented or unfermented food product, being the major consumed pearl millet food product (Fig. 2b) (Adebiyi, Obadina, Adebo, & Kayitesi, 2018). Their consistency range between thick and thin, depending on the concentration of flour (30% down to 10%). Different types of porridges may be prepared by cooking flour in boiling water accompanied by vigorous stirring. In addition, these products can vary greatly in flavor and pH depending on the added ingredient (tamarind extract, lemon juice or potash) (Kajuna, 2001; Taylor, 2016).

Flatbreads are very popular pancake-like gluten-free products that can be made with unfermented pearl millet flour with warm water, like to *Chapati, Rotti* or *Rotla*, typical of India (Siroha, Sandhu, & Kaur, 2016) or, with fermented pearl millet flour like, *Lohoh*, from Saudi Arabia (Osman, 2011). These flatbreads can be cooked on hot plate (*tawa*) or clay griddle or wood fire stove and served at meals, depending on the region, with hot pickle (India) or spicy sauces (Sudam) (Fig. 3). Couscous is a staple food of the North African cuisines and also known as semolina. However, in Senegal and Mali, couscous (*karaw; thiakri, thiacry*) is traditionally made from flour or decorticated pearl millet grains. This couscous is popularly consumed with vegetables or yoghurt (Taylor et al., 2010).

In addition to salted products, pearl millet grains can be used to produce sweets. *Ladoo* and *Dakuwa* prepared small sweet balls (Fig. 2c) from roasted pearl millet grain flours that are typically consumed in India and Nigeria, respectively. According to Singh and Sehgal (2008) and Nkama, Gbenyi, and Hamaker (2015) potentional ingredients such as popped pearl millet grain and malted flour can be added to those sweets for nutritional improvements (Table 4).

Furthermore, pearl millet flour has great potential for developing popular products in other parts of the globe such as ready-to-eat snacks (Balasubramanian, Singh, Patil, & Onkar, 2012), weaning products (Balasubramanian et al., 2014) and non-dairy fermented beverages (Mridula, Sharma, & Gupta, 2015). Moreover, it can be used as an alternative wheat flour substitute in different food preparations, like biscuits, pastas, whole meal breads and kibbeh (Adebiyi, Obadina, Adebo, & Kayitesi, 2018; Awolu, 2017; Brasil, Capitani, Takeuchi, & Ferreira, 2015; Jalgaonkar & Jha, 2016; Maktouf et al., 2016).

Fig. 3. Flatbread (*chapati*) made with pearl millet flour in India. a) flour-water mixture is kneaded to obtain a cohesive dough; b) cooked *chapati* in clay griddle; c) prepared dish of *chapati* in India.

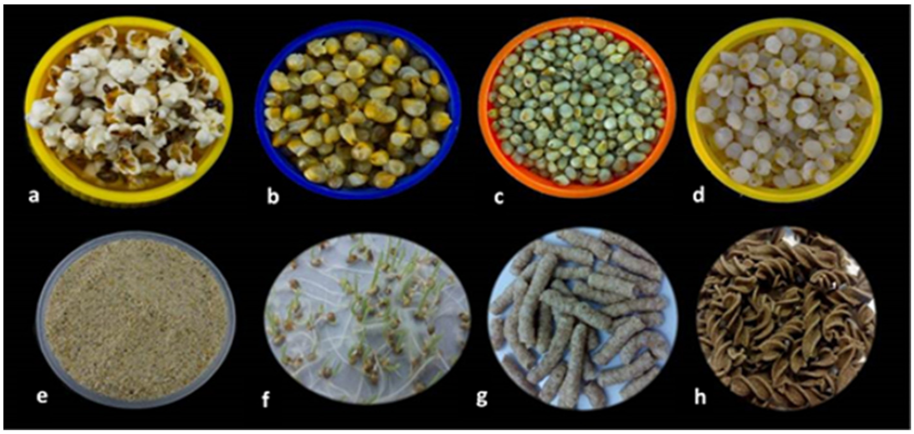

Fig. 4. Potential products to be introduced in Brazil from *Pennisetum glaucum* (L.) R. Br. cultivar BRS 1502. (a) Hot air popped grains; (b) Cooked whole grains; (c) Decorticated grains; (d) Decorticated cooked grain; (e) Whole meal flour; (f) Sprouted grains; (g) Whole grain ready-to eat expanded extrudates; (h) Whole meal pasta. Suggested products made by the authors at Embrapa Food Technology (Rio de Janeiro, Brazil).

8. Conclusions

Based on the information presented, pearl millet grains have great potential as food, due to some relevant nutritional characteristics like: high protein content, dietary fibers and minerals, besides it is considered a low cost crop. In addition, millet has great relevance for guaranteeing food safety, due to the agronomic characteristics of the crop, such as resistance to high temperatures and low rainfall requirements, also the grains have a low incidence of mycotoxins and it is not a transgenic crop.

Furthermore varied types of savory and sweet nutrient products can be made with pearl millet grains and their flours as typical dishes consumed in Africa and India as well as popular products such as biscuits, extrudates, pastas, gluten-free kibbeh and non-dairy probiotic drinks.

Thus, greater incentive on genetic improvement in order to launch new cultivars of high grain yield are needed and evaluate the potential use and benefits of pearl millet in food should be made, because this cereal has significant relevance for food safety as well as being a viable alternative for consumers seeking low priced, nutritious and sustainable food products.

9. Future perspective and challenges to stimulate the consumption of millet as food in Brazil

Despite the fact that Brazil has the third largest number of international publications on agronomic aspects of pearl millet (search based on Scopus®, 2018 abstract and citation database), studies on the potential use of this cereal as food are still scarce in this country. Based on the present review, it seems clear that pearl millet is a viable cereal alternative for Brazilians consumers and also for export if millet consumption demand increases worldwide. As vast Brazilian agricultural lands are currently planted with pearl millet, it is reasonable to say that millet grain production is an agronomic activity to be economically explored. Furthermore, as pearl millet in Brazil has been mainly adopted by the agrobusiness in consortium with known commodities such as maize and soybean, it should be encouraged the production of millet in poor Brazilian lands, particularly in the semi-arid region of the Northeast. In this region, the variability of rainfalls is the primary factor that affects food security, therefore the knowledge of using millet in this region, together with the adequacy of agricultural policies, could expand the options of profitable and nutritious food for both farmers and animal feeding.

In addition, due to the trend towards the development of products with heath and sustainable appeal, pearl millet has great potential to be used as raw material for food preparation of industrial products. Despite the use of pearl millet for food is promising, there are still few drawbacks that need to be overcome, as examples, there is a lack of specific cultivars designed for grain production adapted to different regions and the knowledge of the potential use of millet in the Brazilian diet.

The implementation of public policies that would encourage the cultivation of millet for grain production and, the support of research institutions to promote advanced studies on the development of food products are few examples of great challenges to consolidate the use of millet in Brazil.

In this scenario, as strategies for insertion of millet in Brazilian food, Embrapa (Brazilian Agriculture Research Corporation) has carried out preliminary studies on the chemical composition of the pearl millet (*Pennisetum glaucum* (L.) R. Br., cultivar BRS1502), and development of products based on this cereal, as presented in Fig.4. However, future studies should still be performed to better understand the potential of all pearl millet cultivars produced in the country and also improvement programs of new cultivars suitable for grain production of interesting for food nutrition. These studies should consider the evaluation of nutritional and antinutritional aspects of the grains, as well as studies on the effects of different processes for food use; development of diversified products and sensory assessment; grain and flour lipid stability; clinical essays considering Brazilian diets where hypoglycemic and goitrogenic effects would be studied.

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