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Prospecting the potential for sustainability, nutritional composition, health benefits, and versatile application of millets: Current research and future challenges

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ABSTRACT

Millets, often overshadowed by larger cereal counterparts, are undergoing a renaissance in the realm of nutrition and health. This review delves into their captivating nutritional and nutraceutical potential, uncovering their secrets and highlighting their importance in contemporary diets. Millets emerge as nutritional powerhouses, providing a well-rounded mix of macronutrients, dietary fiber, and plenty of vitamins and minerals. Their significant health benefits include aiding in weight management, controlling glycemic levels, and promoting heart health. Additionally, their antioxidant-rich nature contributes to disease prevention and overall well-being. Notably, millets act as gluten-free champions, offering safe options for individuals with celiac disease and gluten allergenicity. In addition to their nutritional value, millets showcase anti-inflammatory and anticancer properties, paving the way for potential nutraceutical applications. This review also explores culinary innovation, presenting tempting millet-based recipes to seamlessly integrate them into everyday meals, making their inclusion a delightful reality. Additionally, the by-products such as husks and seed coatings obtained from millets are abundant in vitamins, minerals, dietary fiber, and bioactive compounds. Despite the numerous health benefits associated with millets, their full potential remains untapped, with their primary uses revolving around feed and fodder.

1. INTRODUCTION

The food we eat plays an essential role in leading a healthy lifestyle and good well-being. In recent decades, scientists have shifted towards the development of food products that are easily available and contain a good amount of nutrition and functionality. These requirements are fulfilled by underutilized grains like millet grown mostly in India and China and also in some areas in Africa [1]. These were cultivated even before wheat and rice became staple foods and are considered as an important constituent of our daily diet. Different species of millets show different survival variations under a wide range of conditions when seen in contrast to other cereals as they can survive in less fertile soil, high saline environment, high temperatures, and drought areas because of the considerable root system of these grasses which helps them in penetration through deeper soil layers which further helps in drawing out the water and nutrients from deep layers of soil [2]. Millets are small seed grains, have a short cultivation period, require less water, and are highly adaptable to adverse climatic conditions. Millets belong to the Poaceae family and Chlorideae and Paniceae tribes. They are broadly classified as major and minor millets. Major millets include finger millet (*Eleusine coracan*), proso millet (*Panicum miliaceum*), pearl millet (*Pennisetum glaucum*), and foxtail millet (*Seratia italica*). The minor millets include little millet (*Panicum miliare*), kodo millet (*Paspalum scrobiculatum*), barnyard

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millet (*Echinochloa colane*), black fonio (*Digitaria iburua*), teff millet (*Eragrostis tef*), and white fonio millet (*Digitaria exilis*) [3].

Millets are warm-seasoned plants that are generally cultivated for livestock feed and fodder across the globe. Millets are also called coarse grains and are generally called poor man's crops as they are consumed majorly by economically weaker sections of the population in Asian and African countries. Millets only contribute 1% to the world's total production but their significance is much more important in agro-ecosystems. These millets show better productivity on marginal lands as compared to other major cereal crops such as wheat, rice, and so on. These conditions make them favorable to grow in semi-arid areas of Asia and Africa. However, according to geographical regions, the cultivation, consumption, and production of millets may vary. For example, foxtail millet is highly grown in China whereas pearl millet is grown in India, Nepal, Africa, and North America [4]. Millets nowadays are not commercially produced and consumed due to a lack of awareness among people, less area for cultivation and small grain size makes them difficult to process. Due to such reasons, the flour of millet available in the market as compared to other cereal crops is comparatively less.

Millets are rich in proteins, fatty acids, fiber, minerals, vitamins, and other phytonutrients. A balanced amount of necessary amino acids, particularly those containing sulfur (S), is present in millet proteins. Additionally, millets are a rich source of phytochemicals that have been linked to improved health, such as phytocyanins, lignans, phytosterols, polyphenols, and phyto-oestrogens [5]. Various food and beverage products are made from millet such as beer, porridge, bread, and nonalcoholic drinks [6]. Quality and production of millets-based products depend mainly on starch composition, properties, structures, and their interactions with each other. Starch upon hydrolysis with α-amylase produces three types of starch, i.e., resistant starch (RS), slowly digestible starch, and rapidly digestible starch [7]. The RS provides several health benefits such as acting as a prebiotic, it leads to a feeling of fulfilment, escaping digestion, and reaching the colon where it ferments with the help of gut microorganisms thus acting as a prebiotic thereby improving the digestion process [8]. Millets show desirable nutritional attributes and there is increasing interest in their consumption, but millets are still not explored and their utilization is not up to the desired mark, and their information is still scanty in literature.

Food security has been the target all over the world and nutritional security has been added recently. The burden of malnutrition and over nutrition which leads to overweight and obesity is a major issue in today's world as stated and pointed out by Varadharajan *et al*. [9]. Therefore, to ensure food and nutrition security for a diverse and huge population, efforts should be made at the macro and micro levels. In India, considerable efforts are being made at different levels to ensure food and nutrition security. But still, malnutrition prevails and is foreseeable in the future until concerted efforts are made. Millets are high-energy-yielding nourishing food thus helping in addressing malnutrition. Millets are also widely utilized as a source of traditional medicines and is important food for maintaining health [10]. Climate change and crop diversification are the two major points to consider while ensuring food and nutrition security. Millets are underutilized grains that have been neglected for a long time. Millets show maximum productivity in less area of land as they are composed of specific molecular, morphological, and biochemical characteristics that help them to withstand several bad environmental conditions such as pH, poor soil conditions, and drought. They have short stature, small leaves, and short lifecycles and are adaptable to high temperatures, dry weather conditions, and high light conditions, thus these features make millets more efficient than other common cereal crops [11].

2. NUTRITIONAL IMPORTANCE OF MILLETS

Millets also known as first cereals carry 60–70% carbohydrates, 6–19% proteins, 12–20% dietary fibre, 1.5–5% fat, and 2–4% minerals [12]. Millets are also rich in polyphenols, vitamin B, and dietary fibers such as β-glucan, arabinoxylans, hemicellulose, cellulose, and lignans [13,14]. In recent decades, millets have gained worldwide popularity due to the presence of high fiber content, and antioxidants and also become popular as millets are gluten-free, and thus can be consumed by celiac patients. Millets are effective against diabetes, as they lower the release of blood glucose levels [15].

Millets as whole grains and their products are a rich source of vitamins, minerals, fiber, and phytochemicals such as lignans, insulin, phenolics, RS, β-glucan, phytates, and sterols. These plant-derived foods have a positive and synergistic effect on bioactive phytochemicals which are beneficial for healthy outcomes [16]. Millets have nutraceutical properties as they are a rich source of antioxidants, which promote better well-being and prevent the deterioration of human health by reducing the risk of various chronic diseases such as diabetes, cardiovascular diseases (CVD), cancer, and obesity [17]. Millets show an optimistic effect in curing diabetes, atherosclerosis, asthma, gall stone formation, blood pressure, breast cancer, migraine, obesity, and heart attack. Due to such benefits, millets are used as nutraceuticals and functional foods, therefore they are known as "nutricereals" [18].

Millets can contain up to 88% of carbohydrate content depending upon the type of species, variety, crop management, and agroclimatic conditions [19]. Proso and little millet contain high protein as compared to other varieties of millet and protein content are much comparable to major cereal crops, i.e., 10%–15%. Protein content is affected by various agronomic conditions such as environmental growth and soil nitrogen. High protein content makes millet favorable for making value-added food products for malnourished group people. Many major cereals are found to be deficient in lysine, but kodo and finger millet contain 2.2–5.5 g lysine/100 g and 6.5 g/100 g protein is found in pearl millet [20].

Millets contain approximately 1%–6% lipids, contributing to their extended shelf life, particularly due to the removal of germs during decortication [21]. Pearl millet is rich in oil content, i.e., 77.22%, comprising mono and polyunsaturated fats. The oil contains a high amount of linoleic acid (47.5%) and a low amount of linolenic acid (2.15%) as reported by Slama *et al.* [22]. In millets, oleic acid is predominantly found in finger millet, constituting a significant portion of total lipids, followed by linoleic and palmitic acid [23]. Additionally, millets are rich in essential minerals such as sodium, calcium, and magnesium [24].

Kodo millet is the richest source of copper, manganese, zinc, and iron and pearl millet is the rich source of phosphorous and potassium but little amount of iron, zinc, and manganese is present. A deficiency of minerals leads to severe chronic disorders, disruption of tissue structure, and impact on metabolic processes [25]. Proso, finger, foxtail, and barnyard millet contain the highest amount of zinc. Polyphenols found in legumes and cereals show the binding capability to positively charged moieties such as iron, zinc, and calcium, thus intestinal absorption and bioavailability of minerals are greatly influenced as stated by Saldivar [26]. Most of the phosphorous is present in the form of phytic acid or phytate form, thus reducing the availability of phosphorous in the human diet. Mineral content in millets is reduced by milling but the availability of minerals is increased due

to the removal of anti-nutritional factors [27]. Out of the several anti-nutritional factors present in millets, the phytic acid is present in the maximum amount. Its content in millets can be reduced by several processing treatments such as soaking, fermentation, germination, and also by enzymatic treatment with the help of phytase which improves intestinal absorption by releasing the chelated minerals [28].

Millets are also a good source of vitamin B complex except for vitamin B12 and Vitamins are majorly located in the pericarp, aleurone, and bran layer of millets [26]. The riboflavin and thiamin content are 0.05–0.23 and 0.25–0.57 mg/100 g, respectively, in millets. Minor fractions of tocopherols and tocotrienols are also present in millets as reported by Asharani *et al.* [29]. The tocopherol concentration was found between 1.2–4.1 mg/100 g and the highest concentration of tocopherol was found in proso millet, i.e., 3.6 mg/100 g [30]. The major obstacles that confine the growth in the production of millet are insufficient technological and economic support and less investment in research programs that further leads to less utilization of various agronomical techniques, such as mechanization and fertilizers.

3. BRIEF DESCRIPTION OF THE DIFFERENT TYPES OF MILLET

The distinction between major and minor millet is based on their cultivation, usage, morphological and economic importance. Major millets such as pearl millets, finger millet, and foxtail millet are widely cultivated and contribute to global food security, whereas minor millets such as proso millet, kodo millet, and little millet are typically cultivated on a small scale, and are able to survive on adverse conditions such as poor soil fertility, land terrain and limited rainfall areas. Minor millets are considered staple food for tribal people where cultivation of major cereal crops such as wheat, rice, and corn are not popular or fail to yield [31].

3.1. Major Millets

Pearl millet (*Pennisetum glaucum*) is a summer crop and is an erect grass that grows exponentially and attains an average height of 1.5 to 3 cm. The grains are 3 to 4 mm long which is comparably longer than other millet varieties like proso, finger, kodo, foxtail, and little millets. Pearl millets are also called "*nutricereals*" as they contain high amounts of protein, antioxidants, minerals, fiber, and fatty acids [32]. Consumption of fiber-rich foods enhances the good quality of life [33], decreases the chances of occurrence of inflammatory bowel disease [34], and lowers the symptoms of depression [35], and heart problems [36]. In replacement of wheat flour, millet flour can be used in making certain bakery products and functional foods with various homemade ingredients [37].

The finger millet (*Eleusine coracana* L. *Gaertn*.): The finger millet crop is mainly cultivated in Asia and Africa and has great nutritional potential [38]. In the list of millets, finger millets stand in the fourth position globally [39]. Finger millet belongs to the Poaceae family, Chloridoideae sub-family, and the tribe Chlorideae. Finger millet is a yearly grass of a height of 30–150 cm and it finishes its seed cycle in 75–160 days [40]. It possesses a very strong fibrous root system which makes it tough to pull it out from the soil. Finger millets had high nutritional value, 20% dietary fiber, 15-5-8% protein, 1%–2% ether extractives, 65%–75% carbohydrates, and 2.5%–3.5% minerals [21,41]. Finger millet grains contain high amounts of potassium, phosphorus, magnesium, calcium, manganese, copper, zinc, and iron. Its calcium content is 10-fold higher than all other cereals and even three times higher than milk. Finger millet seeds are also rich in cystine, methionine, tryptophan, and total aromatic amino acids as compared to other cereals [42]. Various anti-nutritional compounds present in finger millet such are tannins, phytates, and polyphenols which are present in the seed coat of finger millet grain. These inhibit the bioavailability of micronutrients present in millets. Different treatment methods like soaking, malting, decortication, steaming, popping, fermentation, and germination increase the biological availability of numerous micronutrients found in finger millets [43]. Finger millet is one of the most nutritious cereals and is rich in calcium and iron, the former is helpful in bone strengthening, reducing the risk of bone fracture and the latter is helpful in overcoming anemia [44].

The foxtail millet (*Setaria italica* L.): The foxtail millet is one of the major millet that has the maximum worldwide production. It is ranked at position sixth for the maximal grain yield [45]. It is 2–5 feet long and is cultivated in cool dry areas in comparison to other millets. It taxonomically comes under the *Setaria* genus, family Poaceae and Panicoideae subfamily. It is also known by the names Italian Foxtail, Italian Millet, foxtail bristle grass, and Siberian millet. Foxtail millet grains have a coarse nature and 79% of it is digestible and the remaining part of the grain which is not digested contains high levels of dietary fiber and some anti-nutritional compounds. It also contains crude fibre which is helpful in digestion and helps in improving bowel movement by generating a laxative effect which helps in maintaining a healthy digestive tract. The presence of such bioactive compounds makes foxtail millet an important additive in the preparation of noodles, soups, alcoholic beverages, and pancakes [46,47]. Foxtail millets have a broad range of health-benefiting components and have unique stability of nutrients. The chief constituent of finger millet consists of vitamins, minerals, proteins, fats, dietary fibers, and starch.

3.2. Minor Millets

The proso millet (*Panicum miliaceum L.)* is an ancient summer cereal consumed by humans that was cultivated after cereal crops like wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). It is a short season crop, i.e., 10–11 weeks and is valued for its low water requirement [48,49]. It contains 11.9% moisture, 12.5% protein, 1.1% fat, 1.9% minerals, and 70.4% carbohydrate and essential amino acids, i.e., valine, tryptophan, methionine, phenylalanine, and so on. Quinoa and proso millets resemble each other in seed colour, shape and nutrition [50]. The proso millet is mainly used as food for livestock feed and birds in well-developed countries [48,51]. It contains ample amounts of minerals, proteins, vitamins and micronutrients such as manganese, zinc, copper and iron [52]. The protein content of proso millet is 12.5%, which is slightly higher than other cereals like wheat and rice. Proso millet grains are a better source of essential amino acids such as isoleucine, methionine and leucine as wheat [53,54]. It is also a suitable substrate for beers and distilled liquors and widely used for making the fermented beverages in Asia and Africa.

The kodo millet (*Paspalum scrobiculatum*) was introduced in India about ~3,000 years ago and historically has been an important crop for farming. It is also identified as ditch millet, rice grass, or Indian crown grass mainly grown in India, West Africa, Vietnam, Philippines, and Thailand. This millet contains 12.8% moisture, 8.3% protein, 1.4% fat, 2.6% minerals, 2.47% dietary fiber, and 65.5 % carbohydrates. Several studies represented the utilization of flour made from kodo millet up to the extent of 30%–100% in the making of traditional food products like Dosa, idli, Chappathi, Pongal, cutlet, bread, cookies, and ladoo [55]. Kodo grains are a good stock for malnourishment and is a monocot crop with a grain seed size of 1.5 mm width, and 2 mm length and color may vary from light brown to dark brown and is bound to a

tough husk which is difficult to separate [10]. Kodo millet shows high drought resistance among all the minor millets and produces a good harvest in short growing periods of 80–135 days [50,56]. The dietary fiber found in the outer layer of grain is helpful in promoting several digestive and metabolic processes, such as diminishing the cholesterol and glucose levels in persons suffering from CVD and diabetes [57].

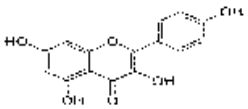
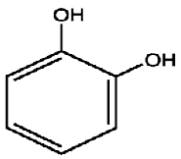
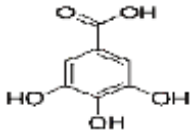
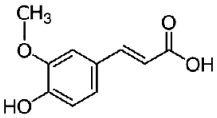
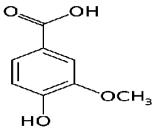
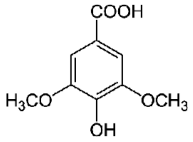
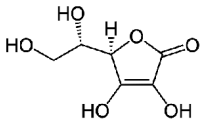
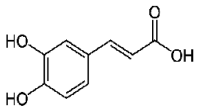
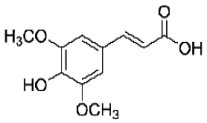
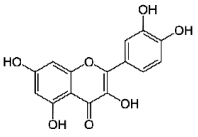
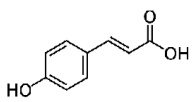
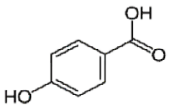
The little millet (*Panicum sumatrense*) was cultivated in India around ~5,000 years ago. It is majorly grown in India, Myanmar, Sri Lanka and Nepal. It contains 11.5% moisture, 7.7% protein, 4.7% fat, 1.5% minerals, 2.53% dietary fiber, and 67% carbohydrates. Little millet is harvested in different parts of India. They have less height and can be cultivated in sandy, loam, slightly acidic, and saline soils. The millets are nutritionally rich grain with a good number of macronutrients and dietary fiber but its utilization is restricted due to the high cost and accessibility of favored cereal grains like rice and wheat which are available at affordable prices. Due to high-fat content, little millet gets rancid early, so various treatments are carried out to enhance the shelf life of grains like blanching, malting, dry heating, and so on. which inactivates the enzymes responsible for rancidity, decreases the level of anti-nutrients and improves digestibility. Little millet is a hard millet, which can grow under adverse agro-climatic conditions [58].

4. BIOACTIVE POTENTIAL AND HEALTH BENEFITS OF MILLETS

Millets are a rich source of bioactive chemicals that have been shown to produce a number of health advantages, including protection against degenerative and chronic diseases associated with contemporary living. The hypoglycemic profile and bioactive composition of millets are the main factors contributing to their prominence as functional ingredients in the development of functional food products [59]. Millets grains are convenient and affordable staple foods with the presence of several natural antioxidants. In comparison to other cereal grains, millet is the richest source of energy. Finger millet contains a higher fat content than other millets, i.e., 3.5%–5.2%, and contains a calcium content of 350 mg/100 g. Millets are rich in iron and phosphorous and several phytochemicals, and bioactive compounds which bestow beneficial health effects to individuals and help in the prevention of various diseases (Table 1) [60]. Millets are rich in various bioactive components having anti-inflammatory, antihypertensive, anti-carcinogenic inflammatory bowel syndrome, atherosclerosis, and contain antioxidant compounds that help in minimizing the risk of heart-related diseases (Table 2). It has been observed that diabetic patients who do not take insulin, and include a millet-based diet in their daily routine helped in reducing plasma glucose levels [61,62]. Millets are naturally gluten-free, which therefore can be served to patients suffering from allergies, intolerances, autoimmune diseases, and intestinal permeability caused due to gluten [63]. Millets are important sources of nutrients and thus play a health-improving role in preventing diseases that are caused due to imbalanced nutrition (Table 3). Millets exhibit various health benefits such as the ability to delay aging, diabetes, cancer, CVD and celiac disease (Table 2). Millets-based food is reported to exhibit longer storage life [64]. As reported by Durairaj *et al.* [65] group of school children who regularly consumed millet-based food diets showed significant increases in weight, height, and hemoglobin levels. The addition of millet and its products to the daily diet can help in maintaining immunity and a healthy lifestyle [71,72] and prevent diseases such as diabetes, coronary heart disease [73] and celiac disease [74].

The major bioactive components present in millets are listed as catechol, kaempferol, ferulic, benzoic, vanillic, gentisic, gallic, cinnamic, sinapic, ascorbic, caffeic, syringic, chlorogenic, and

Table 1. Bioactive compounds found in millet.

Compound	Structure	Reference
Kaempferol		Chandrasekara *et al*. [66]
Catechol		Hithamani and Srinivasan [67]
Gallic Acid		Salar *et al*. [68]
Ferulic acid		Salar *et al*. [68]
Vanillic acid		Hithamani and Srinivasan [67]
Syringic acid		Chandrasekara *et al*. [66]
Ascorbic acid		Chandrasekara *et al*. [98]
Caffeic acid		Hithamani and Srinivasan [67]
Sinapic acid		Hithamani and Srinivasan [67]
Quercetin		Chethan and Malleshi [69]
p-coumaric ac id		Pradeep and Sreerama [70]
p-hydroxybenzoic acid		Pradeep and Sreerama [70]

salicylic acid [68,67,75]. However, several bioactive components can vary in millets depending on their type, cultivars, and environmental conditions. Epidemiological studies suggest increasing the intake of cereal-based foods as it will help minimize the chances of obesity, health symptoms related to age, and various chronic diseases [73]. In rats, there was a decrease in triacylglycerol levels and inflammation after consumption of proso and foxtail millet and its products-based diet for some time [76]. Antioxidants extracted from natural sources show a radical scavenging capacity as that of phytochemicals like flavonoids, tannins, and phenolic compounds, therefore more interest is shown in extracting antioxidants from natural sources [64,77]. Millets are an excellent source of bioactive and nutritious substances, such as flavonoids and polyphenols, which can help prevent and treat a number of diseases and malnutrition. However, because traditional procedures are energy-intensive and might cause thermal deterioration, extracting these beneficial chemicals can be difficult. Green-assisted extraction techniques have shown great promise as efficient and sustainable ways of extracting these bioactive present in millets [78]. Millets are the fourth most important crop that is studied after staple cereal crops for their antioxidant attributes, minerals, and various bioactive components. Bioactive compounds are generally the secondary metabolic product but are considered a major group of radical scavenging compounds [79]. Millet flour helps in managing glucose levels in patients suffering from diabetes and also helps in reducing oxidative stress. Kodo and finger millet showed wound-healing properties as reported by Hegde *et al.* [80] (Fig. 1).

Table 2. Antioxidants found in different millet.

Antioxidants	Major millets	References
Vitamin E	Finger, little, foxtail, proso millets	Asharani *et al*. [29]
Insoluble fibers	Foxtail millets	Bangoura *et al*. [84]
Carotenoids	Little, proso, foxtail, finger millets	Viswanath *et al*. [85]
Tannins	Finger millets	Suma and Urooj [86]
Flavonoids	Pearl, kodo, foxtail, finger, little millets	Suma and Urooj [86]
Phenolic acid	Proso, little, finger, kodo, pearl millet	Okwudili *et al*. [87]
Xylo-oligosaccharides	Finger millets	Devi *et al*. [41]
BHA (Butylated Hydroxy anisole)	Finger millet	Viswanath *et al*. [85]

5. EFFECT OF VARIOUS PROCESSING TREATMENTS ON NUTRITIONAL AND ANTINUTRITIONAL QUALITY OF MILLET

Different processing methods such as thermal processing, fermentation, soaking, and germination/malting are done to increase the availability of micronutrients and also to decrease the anti-nutritional factors such as phytates, tannins, trypsin inhibitors, and so on. Thus, improving the bioavailability of minerals [81]. Millet's decortication is carried out to enhance the sensory properties and texture of food products and also to increase the edibility of the product but decortication reduces some nutrient contents such as fiber and minerals. Therefore, millets are processed before ingestion to improve its nutritional value and enhance its shelf life [82].

Soaking is a popular food preparation technique used for reducing anti-nutritional compounds [83]. Foxtail millet when soaked in distilled water for 12 hours at room temperature represented a significant decrease in anti-nutritional factors such as phytates. However, there was an increase in ionizable zinc and iron thus increasing the nutritional availability of foxtail millets [95].

Germination or malting of cereal grains improves protein digestibility and helps in the reduction of anti-nutrients such as phytic acid, tannins, and polyphenols which interact with protein to form complexes [96]. Malting is practiced at the industrial level for brewing especially in

Table 3. Millet properties, functions and health benefits of millets.

Millet properties	Functions	Health benefits	References
High fiber	Slow release of sugars	Beneficial for diabetic persons; helps in overcoming constipation and helpful in preventing colon cancer	Verma and Patel [88]
Gluten-free	Complex carbohydrate	Best diet ingredient for a person suffering from celiac disease	Rao *et al*. [89]
Nutraceuticals	Anti-microbial Anti-oxidant	Acts as prebiotic; anti-tumerogenic; anti-diabetic; prevent disease risk	Devi *et al*. [44]
Phytochemicals	Phenolic acid and flavonoids	Overall health benefits	Devi *et al*. [44]
Phenolic compounds	Exhibits antioxidant activity and flavonoids are present such as catechin, gallocatechin, epicatechin, and procyanidin	ORAC (oxygen radical absorbance capacity); DPPH radical scavenging assay	Chandrasekara and Shahidi [90]
Anti-cholesterol	Germinated finger millets produce anti hypercholesterolemic metabolites	Helps in the reduction of cholesterol	Venkateswaran and Vijayalakshmi [91]
Antidiarrheal	Natural prebiotic treatment for diarrhea	Helps in maintaining the gut microflora	Lei *et al*. [92]
Epithelialization	Wound healing properties	Increased collagen synthesis, activation of mast cells and fibroblasts	Rajasekaran *et al*. [93]
Nephroprotective properties	Helps in the proper functioning of kidneys in diabetic patients	Decrease in urinary volumes and urinary metabolites.	Shobana *et al*. [94]

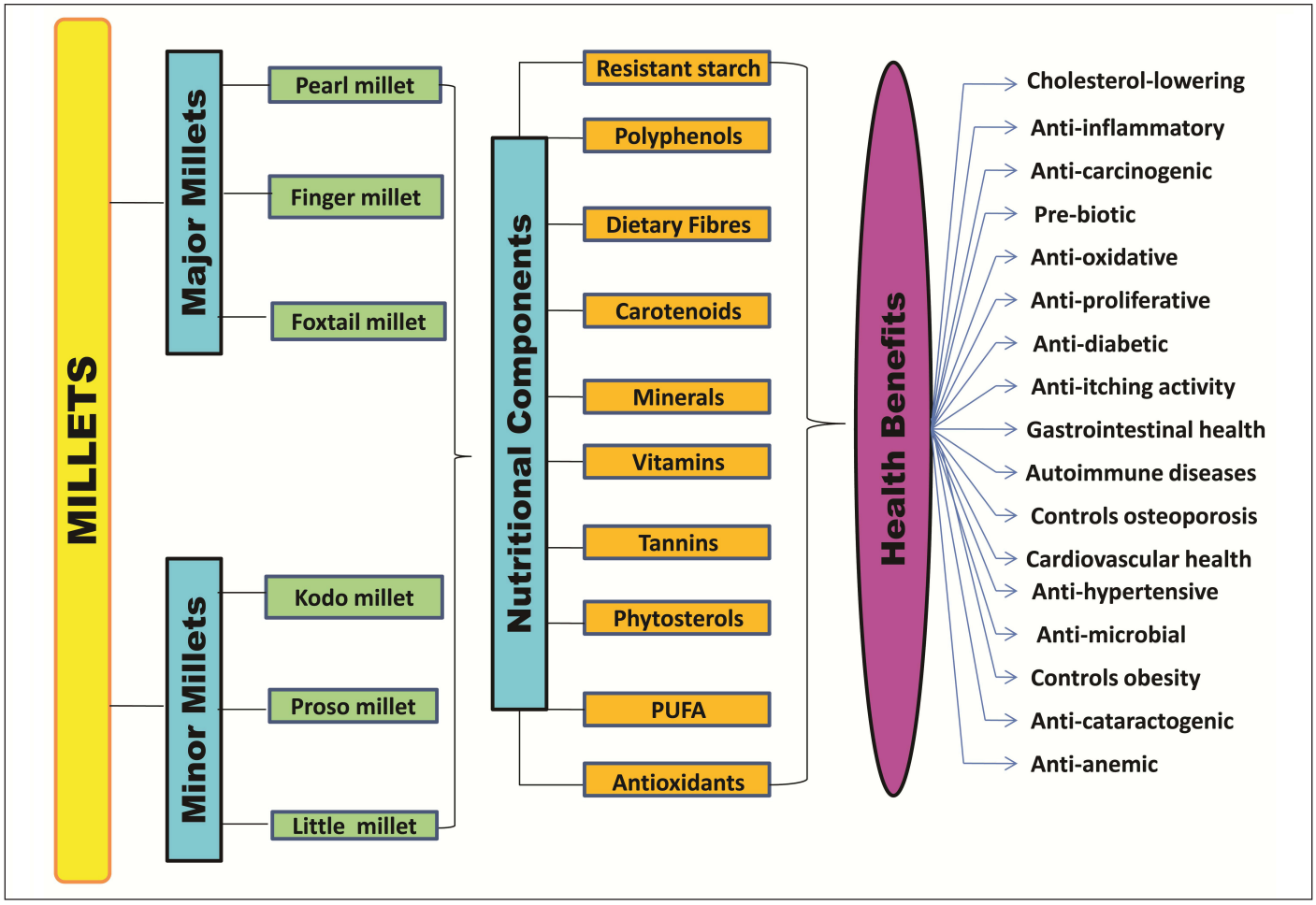


Figure 1. Types of millets, nutritional components and health benefits.

African countries. Masvusvu is a traditional sweet beverage that is made by malting finger millet and another drink is magic, which is a sweet sour product made by natural fermentation of sieved masvusvu in Zimbabwe [97].

Fermentation is widely used as a method of food preservation. It improves the flavors and nutritional properties of raw materials and decreases anti-nutritional factors. Marrisa is an alcoholic drink made in Sudan by using sorghum or millet by fermentation [98]. In Tanzania, finger millets are utilized in making four different types of food, i.e., vtogwa, ugali, uji, and pombe. They are the source for locals and also play an important role in their rituals. Finger millet is also a main ingredient in pombe, which is an alcoholic drink made in Tanzania [99]. Jan, Kumar [100] carried out the fermentation of finger millet (*Eleusine coracana* L.) flour using two strains of *Lactobacillus (Lactobacillus brevis* and *Lactobacillus plantarum) and* yeast (*Saccharomyces cerevisiae* L.). They reported a significant ($p \leq 0.05$) increase in antioxidant activity and a significant ($p \leq 0.05$) decline in the anti-nutritional components such as tannins and phytic acid.

Popping and puffing is a method used for the preparation of ready-to-eat (RTE) products from cereals and legumes. Popped products are porous and crunchy to eat, and taste can be enhanced by adding flavors to them. In popping, grains are exposed to a very high temperature range for the gelatinization of starch. In this method, super-heated vapors are trapped inside the grains causing the expansion of the endosperm instantly, thus breaking off the outer layer. Whereas puffing is the controlled expansion of the kernel, in which the vapor pressure escapes through pores due to high pressure. Popped sorghum is a very famous traditional snack in central India. These grains are mixed with oil and spice or are eaten in a sweetened form. Laddus are prepared from popped sorghum during festival times and as -RTE products [101].

6. PROCESSED PRODUCTS FROM MILLETS

The main products of millet include roti and porridge. Millet flour alone cannot be used in bakery products as millet lacks gluten protein thus dough is not formed. So, the millet flour is treated with hot water that partially gelatinizes the millet starch thus imparting some binding properties to the dough [41]. Multigrain flour is made by blending flours of millet and pulses, thus increasing the nutritional profile of flour as there is an increase in minerals, vitamins, dietary fibers, and proteins. The fortification of finger millet flour in chapatis enhances the taste and helps in controlling glucose levels thus proving beneficial for diabetic patients [102]. The fermentation lowers the anti-nutritional compounds, thus improving taste and increasing the value of food by increasing calcium, protein, and fiber content. Millets can be utilized in making fermented foods like idli and dosa by replacing rice flour with millet flour. In a study conducted by Palanisamy *et al.* [103], they co-fermented the horse gram flour and finger millet flour in different proportions and carried out the natural fermentation and it was observed that the lactic acid bacteria dominated the fermentation

Table 4. By-products obtained after processing of millets.

Processing product	Function	Reference
Hull	Its utilization shows a reduction in LDL cholesterol oxidation inhibition, antiproliferative activity, inhibits liposome oxidation	Chandrasekara and Shahidi [90]
Forage (secondary product) used as animal feed and fuel	The incorporation of crushed grain or whole grain in chicken feed acts as an effective feed ingredient in poultry production	
Seed coat	Plant-based mineral source (calcium, iron and zinc); anti-radical activity and Anti-oxidant activity; seed coat can be utilized in food preservation as it possesses anti-microbial activity	Malleshi [112]; Krishnan *et al*. [43]
Straw	Used in ruminant feeding	Chen *et al*. [113]`
Husk	Production of pellets or briquettes for feedstock	Bappah *et al*. [114]

process. Further, it was observed that reducing sugars get reduced and protein content increased by an increase in amino acids, especially the lysine content. Hence, protein-rich foods can be made with the help of a little addition of millet flour.

In south India, papad is generally consumed in daily diet. It can be made by adding finger millet flour up to 15%–20% along with spices, rice, and black gram flour. For papad preparation, millet flour is cooked in water so that gelatinization of starch occurs, as gelatinization eases up the dough formation. Then, the dough is rolled into thin sheets and cut into desired size and shape and then up to 7% moisture content [104]. Pearl millet grains are utilized in making flakes at high temperatures so that the gelatinization of starch occurs rapidly. Then, the drying of flakes is done till an 18% moisture content range is achieved using heavy-duty rollers. The small size of the millets makes them suitable for flake production. When flakes are added to milk or water, hydration occurs quickly [91]. Extrusion technology is trending nowadays as they are best suited for making RTE products. Kurkure is the best example of extrusion technology. RTE products have become a good choice as a snack food with changes in eating habits [106]. Other examples of extrusion include the consumption of noodles and vermicelli. Noodles are prepared by cold extrusion technology. Noodles nowadays have become convenient food, so noodles can be prepared by using millet flour to increase their nutritional value. Pearl millet grains are soaked in water for 24–48 hours, and then are cooked, extruded, and dried. It produces an excellent product that has a crispy texture when fried and can be utilized as snack food. These food products are pocket-friendly as capital investment is low, and simple ingredients are required for making such products.

Millets have great potential to be included in processed products using modern food processing techniques like extrusion, baking, spray drying, gun puffing, popping, malting, instant mixes, and brewing to develop convenient, RTE, ready-to-cook products, novel food products like meal bars, pellets, muesli, edible films, and analogs of millet milk and dahi. The traditional millet food products include bhat, kheer (sweetened thin porridge), mudde (stiff porridge), roti/chapatti (unleavened bread), idli (fermented savoury cake), dosa (fermented pancake), koozh, koko, togwa, dambu, chhyang, ogi, uji, and brewed drink [107]. Different bakery products such as biscuits, bread, muffins, nankhatai, and so on. can also be prepared by using millet flours. As millet lacks gluten, it is added in fewer ratios as compared to other flour used so that dough can be formed easily. Bread prepared with millet flour showed equal acceptability as that of bread made from wheat flour bread [108]. As reported by Kumar *et al*. [109], they prepared biscuits with the addition of 70% Kodo flour and soy flour, and an increase in the protein content of the biscuits was observed. For the person suffering from celiac disease, the mild flavour and gluten-free properties of proso millet make it ideal for consumption of this millet as bread or other products such as pasta, flour and couscous like products with proso millet which are produced by industries [48].

Millets are used in making roti, dosa, sushi, cookies, and nonyeast pizza. The popular finger millet beverage made in India is Madua [71]. During refrigeration of meat products, deterioration of meat color, flavor, nutritional value, and texture occurs due to lipid oxidation. Thus, by the incorporation of antioxidants-rich millet grains flour, the shelf-life of products is increased by many folds as the scavenging of the oxidized free radical molecule occurs [75]. In West African countries, sorghum or guinea corn which is made from sorghum is generally consumed, especially in Nigeria. Guinea corn is a free-flowing, smooth porridge made from sorghum and wet-milled fermented guinea corn is considered as a probiotic food that is a great source of *Lactobacillus*, *Leuconostoc, Streptococcus* and yeast, *Debaryomyces hansenii.* The nutritional and organoleptic characteristics may vary depending on the production and fermentation period [110].

By-products obtained after the processing of cereals contain ample amounts of potential nutrients and bioactive compounds and thus can act as food additives which are an economical effort to overcome malnutrition and hunger of every economic class of society. These by-products contain several beneficial compounds such as starch, lipids, proteins, dietary fiber, micronutrients, and bioactive compounds. These by-products can be utilized in food industries or can be utilized as feed and fodder. Various by-products obtained from millets are represented in Table 4.

Despite the various nutritional and health benefits of millets, these have not yet gained wide acceptance among people of different sections of society. The major challenges faced by the millet entrepreneurs include a lack of awareness regarding the nutritional importance and variety of millet-based foods available in the market, lack of familiarity, and preparation difficulties, i.e., millet needs cleaning, grinding, and pounding before these can be cooked. Besides sensory attributes such as taste and texture had a significant influence on consumer preferences towards millet and are major barriers to the demand for millet-based foods. Also, many people feel inferior or embarrassed to eat millet, since they think it is a poor man's food [111].

7. CONCLUSION

In conclusion, the use of underutilized grains, particularly millets, provides a fascinating chance for food companies to tackle the urgent issues of food security and health. These grains provide a low-cost source of nourishment and have outstanding characteristics, thereby being ideal for people of various economic levels. Although the fact

that millet is usually utilized as animal feed and fodder, they also possesses the capability to deliver considerable health advantages owing to its capacity to survive tough circumstances and offer yields of substantial nutritional value. Numerous studies have highlighted the health-promoting properties of millets, including dietary fibers, bioactive compounds, antioxidants, proteins, and phenolic compounds. These properties contribute to the prevention of various ailments. Moreover, the incorporation of millet flour improves the color, palatability, and shelf life of products, making them economically viable options, particularly for individuals with limited resources. The bioavailability of key vitamins and minerals in millets could be increased by lowering the level of anti-nutritional substances via different processing processes. Combining millet flour with other types of flour offers the opportunity to generate an array of value-added food products. Although millets can be used and processed to replace key cereal crops, more research and exploration are needed to fully understand the range of benefits they can provide across all areas of food production and consumption. Utilizing underutilized grains like millet, the producers may establish an equitable and ecological food system that tackles the urgent problems of nutrition, food security, and environmental sustainability. It is necessary to appreciate these historical grains and make efforts in research, innovation, and education to assist them in achieving their full revolutionary potential and ensure the long-term sustainability of the planet by working together to create a future in which everyone has access to healthy and economically viable food.

8. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the international committee of medical journal editors (ICMJE) requirements/guidelines.

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10. CONFLICTS OF INTEREST

The authors declare that no financial or any other conflicts of interest exist in this work.

11. ETHICAL APPROVALS

This study does not include experiments on animals or human subjects.

12. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

13. PUBLISHER'S NOTE

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14. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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